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Theoretical to Experimental Examples of Spin Injection Leave Further Challenges

Symposium P, Novel Aspects of Spintronic Materials and Devices, provided an overview of challenges and recent progress in controlling the spin degrees of freedom in solid-state systems. It is instructive to think of a spintronics scheme as consisting of three different stages: generation of spin polarization, spin manipulation, and spin detection. Spin polarization can be defined as the ratio of the sum and the difference of spin-resolved components (spin-up and spin-down) of a particular quantity such as charge current, carrier density, or the density of states. While many materials in their ferromagnetic state can have a substantial degree of equilibrium carrier spin polarization, this alone is not sufficient for spintronic applications that typically require current flow and/or manipulation of the nonequilibrium spin (polarization).

A large part of the symposium focused on the issues related to spin injection where, by driving electrical current across the interface between magnetic and nonmagnetic material, nonequilibrium spin polarization is introduced in a nonmagnetic material. Detailed theoretical considerations were presented by R.H. Silsbee (Cornell) and E.I. Rashba (SUNY—Buffalo). Experimental reports on spin injection spanned a wide range of materials, from organic semiconductors (C. Taliani, ISM, Bologna, Italy) to HTSs (J. Wei, Univ. of Toronto). It was shown that metallic ferromagnets combined with a tunneling barrier can provide efficient room-temperature spin injection into common semiconductors such as GaAs (B.T. Jonker, NRL and V.I. Safarov, Univ. Aix-Marseille II, Marseille, France).

An alternative method to inject spin into GaAs was discussed by S.S.P. Parkin (IBM Almaden Research Center). His technique employed a magnetic tunneling transistor, which is a three-terminal device combining a magnetic tunnel junction with a semiconductor collector.

However, many materials challenges remain: A substantial injection of spin into silicon has yet to be demonstrated and the race to fabricate a reliable room-temperature ferromagnetic semiconductor continues.

Symposium Support: ONR.

Report: Symposium P, Novel Aspects of Spintronic Materials and Devices
Supported by the US ONR Grant N00014-02-0816 and the MRS

The four day program provided an overview of challenges and recent progress to control the spin degrees of freedom in solid state systems. The selection of invited speakers reflected the interdisciplinary nature of the field and diverse requirements imposed on promising materials candidates for future spintronic devices. Speakers included both the experts in the studies of (ferro)magnetic properties of semiconductors, which have only recently begun, as well as the experts in more traditional ferromagnetic materials. While semiconductors are the basis for a well-controlled manipulation of charge-based properties (and simplify the issue of compatibility with conventional electronics), a substantial generation of nonequilibrium spin polarization (desirable even at room temperature for spintronic devices) and robust ferromagnetism is typically provided by metallic ferromagnets. These considerations lead naturally to the two different directions of investigation addressed at the symposium. On one hand it is important to resolve the key issues in the hybrid structures (combining semiconductors with other materials, usually ferromagnetic metals). The role of interfaces (E. I. Rashba) and surface reconstruction [which reduces nominally a high bulk spin polarization] (R. A. de Groot), efficient spin injection and reliable spin detection (a series of speakers V.I. Safarov, B.T. Jonker, P. A. Crowell, G. Schmidt, C. M. Marcus, and D. Weiss) have been addressed. One of such hybrid structures the magnetic tunneling transistor which combines a standard magnetic tunnel junction with GaAs (discussed by S.S.P. Parkin) attracted a substantial attendance of the participants from the Symposium Q on Magnetoelectronics. A recent advance in developing this device is that now there is a reliable detection of spin-polarized hot carriers (injected across the Schottky barrier into a semiconductor) using a spin LED. On the other hand it is important to examine what the implications are of injected (nonequilibrium) spin and the device potential of all-semiconductor structures. Femtosecond scale spin relaxation of holes in GaAs was quantified by D. J. Hilton and a proposal for bipolar spintronics, including a spin transistor (with a spin and magnetic field controlled current gain) was discussed by J. Fabian. Issues related to ferromagnetic semiconductors ranged from the light and electric control of ferromagnetism (Y. Ohno, A. Oiwa) to the limitations of the standard mean field picture (A. Zunger, R. Bhatt).

While the term spintronics was coined rather recently, related research dates back many decades. Symposium P involved several pioneering contributors (R.H. Silsbee, E. I. Rashba, and V. I. Safarov, with the discoveries ranging from early work on electrical spin injection, spin-orbit coupling, and optical spin orientation in GaAs, respectively) who provided important, yet often overlooked, historical background together with their assessment of the current challenges in the field. The symposium ended by focusing on organic materials including the first report of electrical spin injection into an organic semiconductor (C. Taliani) and the new class of organic ferromagnets (N. P. Raju). Interestingly, these results were at the core of the DARPA workshop on organic spintronics, (April 2003, Baltimore). The Symposium program also provided useful feedback to the chairs (B. T. Jonker and J. De Boeck) of a large upcoming conference Spintech II (August, Brugge, Belgium) who were active participants.

A class of open questions, raised at the Symposium, is related to more realistic modeling of semiconductor devices. For example, challenges includes exploiting the effects of material inhomogeneities, detailed understanding of interfacial effects and a combination of highly nonlinear current-voltage characteristics with realistic electronic structure calculations. An international workshop on these topics is planned to take place in Spring 2004 at the University of Maryland. One of the Symposium P organizers (I. Zutic) used the opportunity of interacting with the Symposium participants to better address the topics which will be published in the Reviews of Modern Physics as a sixty page paper on spintronics.

2002 FALL MEETING

BUDGET SUMMARY

SYMPORIUM P

SPONSORS:			Received
MPS		\$1,000.00	
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LAST NAME	FIRST NAME	REG	PROC	TRAVEL	PROMOTION	A/V	FOOD	TOTAL
Akinaga +	Hiro	\$450.00						\$450.00
de Groot +	Robert A.	\$450.00						\$450.00
Fabian +	Jaroslav	\$450.00		\$20.00				\$470.00
Ohno	Yuzo	\$375.00						\$375.00
Oiwa	Akira	\$450.00						\$450.00
Rashba	Emmanuel	\$105.00						\$105.00
Safarov	V.I.	\$450.00						\$450.00
Schmidt	Georg	\$450.00						\$450.00
Taliani	Carlo	\$450.00						\$450.00
Wei	John	\$450.00						\$450.00
Weiss	Dieter	\$450.00						\$450.00
Zutic	Igor	\$450.00						\$450.00
ONR								\$0.00
Process O/Site								\$0.00
TOTAL		\$4,980.00	\$0.00	\$20.00	\$0.00	\$0.00	\$0.00	\$5,000.00

SYMPOSIUM P
Novel Aspects of Spintronic Materials and Devices

December 2 - 5, 2002

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* Invited paper

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SESSION P1: SPIN INJECTION

Chair: Igor Zutic

Monday Morning, December 2, 2002
Room 204 (Hynes)

9:00 AM *P1.1

DETECTION OF CURRENT INDUCED SPIN POLARIZATION.
Robert H. Silsbee, Cornell University, Department of Physics, Ithaca, NY.

In systems without inversion symmetry spin-orbit interactions give rise to a spin-splitting, proportional to the electron wave-vector, of the one-electron states. Driving an electric current through such a system establishes a non-equilibrium spin polarization of the electrons. Possible means of detection of this polarization will be noted. Of particular interest is its detection, in two dimensional electron systems, through use of ferromagnetic probes to sample the spin dependent distortions of the Fermi surface. Limiting cases will be described to elucidate the physics. If time permits, the relation of these experiments to issues of efficiency of spin injection will be discussed. The audience will be asked to decide whether a current can be established in a loop containing such a sample in which spin polarization is established by application of an external magnetic field.

9:30 AM *P1.2

SPIN INJECTION THROUGH RESISTIVE CONTACTS.
Emmanuel I. Rashba, The State University of New York, Department of Physics, Buffalo, NY.

Because of the conductivity mismatch between metallic leads and semiconductor microstructures, using resistive spin-selective contacts is a necessary condition for the efficient spin injection from a metallic ferromagnet (F) into a semiconductor (S). Equations describing spin transport across a F-S-F-junction with such contacts are rather cumbersome even in the standard diffusive approximation. A convenient technique based on choosing the spin injection coefficients through different interfaces as the basic variables was developed; it simplifies essentially the derivations and many of the final equations. New results derived in this way for the resistance of a F-N-F-junction and the spin valve effect will be presented. In particular, spin injection through spin-conserving contacts always increases the resistance of a F-S-F-junction. The frequency dependence of the resistance, $R(\omega)$, and of the capacitance, $C(\omega)$, of a F-S-junction is found. It can be applied for non-destructive all-electrical measuring the basic parameters of a junction. Specific properties of spin non-conserving junctions and spin injection into a ballistic S-region will be discussed. Electrical screening is critically suppressed in low-dimensional conductors with strong space quantization. Their unique transport properties include non-local relation between the conductivity and the electric field and giant capacities of inhomogeneous conductors.

10:30 AM *P1.3

HIGHLY EFFICIENT SPIN INJECTION IN FERROMAGNETIC METAL / INSULATOR / SEMICONDUCTOR TUNNEL STRUCTURES. V.I. Safarov, CPEC, Department of Physics, University Aix-Marseille II, Marseille, FRANCE; V.F. Motsnyi, J. De Boeck, P. van Dorpe, W. van Roy, and G. Borghs, IMEC, Leuven, BELGIUM; E. Goovaerts, University of Antwerpen, Antwerpen, BELGIUM.

We demonstrate experimentally the electrical spin injection in FM / insulator / semiconductor tunnel Spin-LED heterostructures [1]. With the in-plane magnetized FM, the electrons have in-plane spin orientation, so the polarization of injected electrons in a surface emitting LED cannot be directly monitored by circular polarization of the luminescence. For optical assessment of spin injection, we introduce Oblique Hanle Effect technique: by applying a moderate (<0.5 T) oblique external magnetic field the spin orientation within the semiconductor can be manipulated to have a non-zero out-of-plane component. The NiFe / CoFe / AlOx / GaAlAs / GaAs spin-LED heterostructures were fabricated. The injected spin polarization of 21-29% was currently observed at 80 K [2]. From the TMR measurements with the same ferromagnetic layers, we estimate the electron polarization in our FM/AlOx injector being 40% at 80 K (30% and RT). Thus with the hybrid tunnel structure we achieved a very high efficiency of the spin injection. The spin injection persists at room temperature; a 5% steady state spin polarization was measured [2]. However this reduction does not indicate the loss in spin injection efficiency, it is essentially due to strong enhancement of spin relaxation rate within semiconductor at this temperature, what was confirmed by Oblique Hanle Effect measurements. The introduction of oxide layer in a Spin-LED overcomes technological difficulties related to magnetically dead layer formation and interdiffusion at the FM/semiconductor interface. It does not require epitaxial growth of the FM and a large variety of ferromagnetic materials can be deposited on top of the oxide layer, forming a universal spin source. The Oblique Hanle effect permits optical assessment of spin injection and provides additional information about spin kinetics within the

semiconductor. [1] Motsnyi et al, *Appl.Phys.Lett.* July 1, 2002 [2] To be published.

11:00 AM *P1.4

SPIN INJECTION AND SCATTERING IN SEMICONDUCTOR HETEROSTRUCTURES. B.T. Jonker, A.T. Hanbicki, G. Kioseoglou, R.M. Stroud and A. Petukhov[†], Naval Research Laboratory, Washington, DC; G. Iftikos, R. Mallooy and A. Petrou, State University of New York, Buffalo, NY; [†]South Dakota School of Mines & Technology.

Efficient electrical injection of spin-polarized electrons from a contact into a semiconductor is a critical issue for future semiconductor-based spintronic devices. Spin injection from semimagnetic semiconductor contacts (ZnMnSe/AlGaAs/GaAs) has produced electron spin polarizations of ~85% in the GaAs QW [1]. Several factors potentially limit spin transport across heteroepitaxial interfaces. We show that the stacking fault density at the contact interface correlates inversely with spin injection. A theoretical treatment shows that the suppression of spin injection is due to enhanced spin-flip scattering at this common defect, and provides excellent agreement with the data. The desire for room temperature operation leads one to consider other materials and avenues. Ferromagnetic metals offer high Curie temperatures and can be rapidly switched at low fields. We report spin injection from an Fe Schottky contact into an AlGaAs/GaAs LED structure [2], producing QW spin polarizations of 16%. These robust effects are attributed to spin tunneling [3] through the tailored Schottky barrier contact. The width of the depletion region at the Fe/AlGaAs interface is controlled by the semiconductor doping profile. Under reverse bias, electrons tunnel from the Fe into the semiconductor and radiatively recombine in the GaAs QW. The circular polarization of the surface emitted electroluminescence provides a quantitative measure of the QW spin polarization [1]. The spin tunnel current is dominated by minority spin carriers. These results will be compared with previous work [4] and modeling of Schottky barrier injection. Schottky tunnel barriers thus provide a routine contact pathway for the integration of spin transport into existing semiconductor processing technology.

Work supported by ONR and DARPA.

[1]. Fiederling et al, *Nature* (1999); Jonker et al, *PRB* (2000), *APL* (2001). [2] Hanbicki et al, *APL* (2002). [3] Rashba, *PRB* (2000). [4] Zhu et al, *PRL* (2001).

11:30 AM P1.5

SPIN DETECTION IN FERROMAGNET-SEMICONDUCTOR SCHOTTKY DIODES. J. Strand^a, A.F. Isakovic^a, C.J. Palmström^b, and P.A. Crowell^a, ^aSchool of Physics and Astronomy, ^bDepartment of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN.

Several recent experiments have used electroluminescence (EL) polarization as a detector of spin-polarized carriers that are injected into a semiconductor heterostructure electronically. When the source is a ferromagnetic metal, the carriers are injected through a Schottky barrier, and a quantum well (QW) n-i-p diode serves as the detector. [1] We have completed a series of polarization-resolved EL measurements on metallic ferromagnet-semiconductor light-emitting diodes showing polarization signals up to 11% at 2 T. The magnetic field dependence of the EL polarization tracks the perpendicular component of the magnetization of the Fe electrode. The maximum polarization signal observed from non-magnetic control samples is 3% at 5 T, and the maximum magneto-absorption contribution is approximately 2%. Although these results are strongly suggestive of electronic spin injection from Fe into the semiconductor heterostructure, systematic EL and photoluminescence (PL) measurements as a function of bias voltage address several open questions. The largest polarization signals are observed over a relatively narrow range of bias voltage in samples that use p-doped $Al_xGa_{1-x}As/GaAs$ quantum wells as detectors. The dominant contribution to the EL spectrum in this bias range is a peak approximately 20 meV below the ordinary ground-state recombination in the quantum well. At larger bias voltages, which yield a typical quantum well EL spectrum, the maximum polarization signal is only 4%. Optical pumping demonstrates that the QW recombination peak has a spin detection efficiency of order 25-50%, and so the low QW polarization signal in EL measurements cannot be attributed entirely to a long carrier recombination time. In contrast, the low-energy EL peak that yields the large polarization signal cannot be detected in PL, and the origin of its higher spin-detection efficiency remain unclear. This work was supported by DARPA/ONR-N/N00014-99-1005, and N/N00014-01-1-0830, ONR N/N00014-99-1-0233, and NSF MRSEC 98-09364. [1] H. J. Zhu et al, *Phys. Rev. Lett.* 87, 016601 (2001); A. T. Hanbicki et al, *Appl. Phys. Lett.* 80, 1240 (2002).

SESSION P2: SPIN INJECTION AND
RASHBA EFFECT

Chair: Paul A. Crowell
Monday Afternoon, December 2, 2002
Room 204 (Hynes)

1:45 PM *P2.1

SPIN-INJECTION FROM HALF-METALS AT FINITE
TEMPERATURES. L. Chioncel, A.I. Lichtenstein, M.I. Katsnelson,
ESM, NSRIM, KUN, Nijmegen, THE NETHERLANDS; G.A. de
Wijs, R.A. de Groot, IGM-CMS, Nijmegen, THE NETHERLANDS.

Injection of spin-polarized charge carriers into semiconductors requires the preservation of the semiconducting properties for one spin-direction throughout the interface. This is particularly important at finite temperatures, where the interaction of interface states with non-quasiparticle states due to (virtual) magnon excitations can have a detrimental influence on the performance. Results of computational studies focussing on the optimization of the interface in relation to spin-injection at finite temperatures will be presented.

2:15 PM P2.2

SPIN-DEPENDENT CURRENT IN SEMICONDUCTOR
ASYMMETRIC SUPERLATTICES. C. Moyses Araujo and
A. Ferreira da Silva, Universidade Federal da Bahia, Instituto de
Fisica, Bahia, BRAZIL; E.A. de Andrade e Silva, Instituto Nacional
de Pesquisas Espaciais-INPE, Sao Paulo, BRAZIL; C. Persson and R.
Ahuja, Uppsala University, Department of Physics, Uppsala,
SWEDEN.

The electron spin-filter is one of the most promising component in the spintronic technology. However, despite the fast growing research, and many proposals, there is still no definite experimental realization of such semiconductor device yet. A spin-filter device using nonmagnetic triple barriers III-V semiconductor structures has been proposed recently[1]. It is based on the effect of electron spin polarization by resonant tunneling[2] due to the Rashba spin-orbit coupling. As a result of such coupling, it has been demonstrated that formations of spin-dependent conduction minibands exist in the case of asymmetric superlattice, with asymmetric double-barrier unit cells[3]. We have studied here the spin-dependent current for such superlattices. The specific results for InGaAs based asymmetric structures with different pairs of lattice-matched barriers materials (InP, InAlAs, and GaAsSb) are shown. [1]T. Koga, J. Nitto, H. Takayanagi, and S. Datta, Phys. Rev. Lett. 88, 126801 (2002). [2]E. A. de Andrade e Silva and G. C. La Rocca, Phys. Rev. B 59, R15583 (1999). [3]C. Moyses Araujo, A. Ferreira da Silva, and E. A. de Andrade e Silva, Phys. Rev. B 65, 235305 (2002).

3:00 PM *P2.3

MESOSCOPIC SPINTRONIC DEVICES. Charles M. Marcus,
Department of Physics, Harvard University, Cambridge, MA.

Recent experiments in which both phase coherence and spin are important will be discussed. We investigate spin-orbit effects and spin injection and detection in mesoscopic GaAs quantum dots and quantum point contacts. We also discuss mesoscopic spin pumping, a technique that uses quantum coherence to generate a spin current without any charge current.

3:30 PM *P2.4

TENSILE STRAIN ENHANCEMENT OF THE EXTRAORDINARY
MAGNETORESISTANCE OF METAL/SEMICONDUCTOR
COMPOSITE STRUCTURES AND THE DISCOVERY OF
EXTRAORDINARY PIEZOCURRENT. A.C.H. Rowe, NEC
Research Institute, Princeton, NJ. (In collaboration with D.R. Hines
and S.A. Solin).

Composite metal/semiconductor structures have received a great deal of attention recently because they exhibit 'extraordinary' magnetoresistance (EMR) in perpendicular magnetic fields [1]. In this talk I will present data on enhancement of the EMR via the application of uniaxial tensile strain [2], and comment on the importance of this result for MR sensor applications. Of greatest interest in this work is the discovery of a second 'extraordinary' effect extraordinary piezocurrent (EPC). EPC of composite structures has been measured to be more than 5 times greater than the piezocurrent of the homogeneous semiconductor alone. Like EMR, the magnitude of the EPC depends strongly on the unstrained sample geometry and is a result of changes to the current distribution at the metal/semiconductor interface under the influence of the external perturbation. In the case of EMR, the current at the interface is deflected away from the metal due to the appearance of a Hall angle in an applied field [1]. On the other hand, EPC is a result of a reduction in interface barrier resistance with tensile strain [3] that allows the current to better sample the metal as the strain is increased. In light of this result, one might reasonably expect an entire family of

'extraordinary' effects in composite materials, and I will present several possibilities. Finally, I will briefly discuss recent interest in experimenting with ferromagnetic shunt metals in EMR structures. [1] S.A. Solin, Tineke Thio, D.R. Hines and J.J. Heremans, Science 289, 1530 (2000).

[2] A.C.H. Rowe, K. Fasanella, D.R. Hines, T. Zhou and S.A. Solin, Rev. Sci. Instr., in press

[3] C.S. Gworek, P. Bharak, B.T. Jenker, E.R. Weber and N. Newman, Phys. Rev. B 64, 045322 (2001)

4:00 PM P2.5

SPIN POLARIZATION IN SEMICONDUCTOR HETERO-
STRUCTURES. Jacek A. Majewski, Peter Vogl, Walter Schottky
Institute, Technical University of Munich, Garching, GERMANY.

We present detailed theoretical studies of the zero field spin splitting in semiconductor heterostructures. The spin splitting determines the precession frequency of the electron spin and plays a crucial role in explaining the major spin relaxation mechanisms. We have studied spin splitting energies of conduction and valence bands of several common-atom (GaAs/AlGaAs, InAs/AlAs) and no-common-atom (AlSb/InAs, GaSb/InAs, AlSb/InP) short period superlattices and quantum wells (grown in the [001] direction) by performing fully relativistic pseudopotential local density functional calculations, augmented by tight-binding studies for very large systems. We show that the dependence of the bulk inversion asymmetry (BIA) and Rashba contributions to the zero field splitting on the interface native asymmetry, on the electric field and on the well width follows universal trends. In the symmetric common-atom structures, the zero field splitting consists entirely of the BIA terms which decrease inversely with the well width. The presence of an electric field increases the BIA term considerably in systems of a well width above 5nm (e.g., by a factor of five in AlAs/GaAs/AlAs with a well width of 8 nm and an electric field of 120 kV/cm). This fact has been overlooked in previous calculations based on the envelope-function theory. For a given value of the electric field, the Rashba constant increases in proportion to the well width, but saturates for well widths larger than 7 nm. In the no-common-atom heterostructures, the Rashba constant originates solely in the interface native asymmetry and decreases with well width. In short period superlattices, the Rashba effect is determined by the local microscopic structural details of the interface rather than the macroscopic electric field. For wide wells, however, both the Rashba and BIA constants markedly increase when an electric field is applied. We find generally the spin splittings in InAs and GaSb wells to be typically larger than in GaAs wells by a factor of 6-7. We can explain this trend in the framework of an analytical tight-binding model. Using the obtained spin splitting constants, we discuss the corresponding spin relaxation rates.

4:15 PM *P2.6

INTERBAND TUNNELING OF SPIN POLARIZED ELECTRONS
IN p-(Ga,Mn)As/n-GaAs HETEROJUNCTIONS. Y. Ohno, M.
Kohda, K. Takamura, F. Matsukura, and H. Ohno, Tohoku Univ.
Research Institute of Electrical Communication, Sendai, JAPAN.

We demonstrate electrical injection of spin polarized electrons via interband tunneling in ferromagnetic/nonmagnetic semiconductor Esaki diodes. An interband tunnel junction consisting of ferromagnetic p⁺-(Ga,Mn)As and nonmagnetic n⁺-GaAs/n-GaAs under reverse-bias allows spin-polarized tunneling of electrons from the spin-split valence bands of (Ga,Mn)As to the conduction band of n⁺-GaAs/n-GaAs. The spin polarization of tunneled electrons is probed by analysis of the degree of circular polarization of electroluminescence (EL) from an n-GaAs/InGaAs/p-GaAs n-i-p junction integrated with the ferromagnetic tunnel junction. Clear hysteresis loop with $\pm 6.5\%$ remanence is observed in the magnetic field dependence of the EL polarization at 6 K, indicating a possible application of p-type ferromagnetic semiconductors as a spin polarizer for conduction electrons.

SESSION P3: SPIN INJECTION AND
APPLICATIONS

Chair: Berend T. Jonker
Tuesday Morning, December 3, 2002
Room 204 (Hynes)

9:00 AM *P3.1

SPIN INJECTION IN LINEAR AND NON-LINEAR RESPONSE.
Georg Schmidt, Physikalisches Institut, Universität Würzburg,
Würzburg, GERMANY.

Spin injection from dilute magnetic semiconductors into non magnetic semiconductors is now well established experimentally. It was demonstrated both in an electro-optical experiment [1] and also in a transport experiment that exhibited a novel large magnetoresistance effect (LMR)[2]. This latter effect results from a reduction of the

conductivity of a non magnetic semiconductors by the suppression of one of the two available spin channels. Electrical spin-injection into a non-magnetic conductor results in a splitting of the electrochemical potentials for spin-up and spin-down at the interface between magnet and non magnet. This holds for metallic systems, as well as for semiconductors. In an all metal system the splitting is typically of the order of microvolts and will thus not influence the electron system which has a Fermi energy of several volts. In an all semiconductor system however, the splitting can rapidly increase to several mV and thus become of the order of magnitude of the Fermi energy, leading to strongly non-linear effects. Experiments show, that the LMR effect decreases rapidly when applying a bias voltage larger than about 1 mV. Besides the experimental results we will present a theoretical model which describes the non-linear behaviour of a DMS/NMS interface and which is in good agreement with the experimental results. We will also discuss the implications for devices based on spin injection and the differences to the non linear effects recently described by Zhu et al.[3], [1] R. Fiederling et al. *NATURE* 402, 787 (1999) [2] G. Schmidt et al. *Phys. Rev. Lett.* 87, 22703 (2001) [3] Z.G. Yu et al. *Cond-mat/0201425*

9:30 AM *P3.2
BIPOLAR SPINTRONICS. Jaroslav Fabian, Karl-Franzens Univ Graz, Graz, AUSTRIA.

Bipolar spintronics [1-4] refers to fundamentals and applications of spin-polarized transport carried by both electrons and holes in generally inhomogeneously doped (with donors, acceptors, and with magnetic impurities) semiconductors. Primary examples of bipolar spintronics are devices like spin-polarized solar cells [1,2] and magnetic $p - n$ junctions [3]. In the talk I will formulate theory [4] of spin-polarized bipolar transport in inhomogeneous semiconductors as carrier recombination and spin relaxation limited drift and diffusion, and introduce the concepts of the spin-polarized solar cell and the magnetic $p - n$ junction. In the context of those devices I will discuss the fundamental problem of spintronics, namely spin injection, here the spin injection through the space-charge region (depletion layer). I will argue that the proposed spin bipolar devices have great technological potential, mainly due to their nonlinear spin-charge coupling, an effect leading to very large (in principle greater than 1000%) giant magnetoresistance [3,4]. Spin-charge coupling in bipolar transport through $p - n$ junction will be also shown to lead to spin amplification [1], spin capacitance [2], and a spin-valve effect [3,4].

References:

- [1] I. Žutić, J. Fabian, and S. Das Sarma, *Phys. Rev. B* **64**, 121201 (2001).
- [2] I. Žutić, J. Fabian, and S. Das Sarma, *Appl. Phys. Lett.* **79**, 1558 (2001).
- [3] I. Žutić, J. Fabian, and S. Das Sarma, *Phys. Rev. Lett.* **88**, 066603 (2002).
- [4] J. Fabian, I. Žutić, and S. Das Sarma, preprint cond-mat/0205340. presentation of research in collaboration with I. Žutić and S. Das Sarma, and supported by DARPA, US ONR, and NSF.

10:30 AM *P3.3
SPIN-POLARIZED TUNNELING THROUGH SINGLE-CRYSTAL GaAs BARRIERS. S. Kreuzer, J. Moser, M. Zenger, W. Wegscheider, D. Weiss, Experimentelle und Angewandte Physik, Universität Regensburg, Regensburg, GERMANY.

We investigate spin-dependent transport through an epitaxial GaAs barrier sandwiched between polycrystalline iron films. Electron transport through the barrier is dominated by quantum mechanical tunneling, demonstrated by a nonlinear I-V-characteristic, an exponential dependence of the tunneling current on the barrier thickness and the temperature dependence of the current. Though small a clear tunneling magnetoresistance effect proves spin-dependent transport through the Fe-GaAs interface. The small size of the effect and the high-field magnetoresistance suggest that spin flip scattering plays a decisive role in transport. The current state of the experiments will be reviewed.

11:00 AM *P3.4
MAGNETIC TUNNEL TRANSISTORS: A SOURCE OF HIGHLY SPIN POLARIZED ELECTRON CURRENT. Stuart S.P. Parkin, Xin Jiang, Sebastiaan van Dijken, Roger Wang, Bob Shelby, Roger MacFarlane, IBM Research Division, Almaden Research Center, San Jose, CA; Glenn Solomon and James Harris, Solid State Photonics Laboratory, Stanford University, Stanford, CA.

We show that a magnetic tunnel transistor (MTT) provides a source of nearly 100% spin polarized electrons through spin filtering in ferromagnetic thin films. The MTT is comprised of a tunnel junction married to a semiconductor collector. Electrons are injected from a ferromagnetic or non-magnetic emitter across a tunnel barrier into a metallic base layer, comprised of one or more ferromagnetic layers, formed on GaAs. A Schottky barrier is formed at the

base/semiconductor interface. The energy of the injected electrons is varied by applying a voltage across the tunnel barrier. When the electron energy exceeds the height of the Schottky barrier a collector current is measured. The collector current depends on the relative alignment of the magnetization of the ferromagnetic layers in the emitter and base layers. Magneto-collector current changes exceeding 3400% are observed at 77K. Features in the energy dependence of the collector-current and the magneto-collector-current can be modeled in detail by assuming a significant spin-dependent broadening of the electron energy distributions through inelastic scattering in the base layer plus substantial angular broadening of these distributions. Finally, we explore the spin polarization of the collector current in the GaAs collector by measuring the polarization of light emitted from a GaAs quantum well heterostructure on which the MTT is deposited through metal shadow masks.

11:30 AM *P3.5
FABRICATION OF NANOSCALE PERMALLOY-SILICON STRUCTURES IN SPIN VALVE GEOMETRY. S. Hacia, T. Last, S.F. Fischer and U. Kunze, Werkstoffe und Nanoelektronik, Ruhr-University Bochum, Bochum, GERMANY.

Magnetotransport studies are performed on a nanoscale ferromagnet-SiO₂-degenerate Si(100) tunneling device in spin-valve geometry. The ferromagnetic contacts are realized as highly remanent, single domain Permalloy (Py) nanostructures for which a sufficient degree of spin polarization anticipated. According to micromagnetism, different widths (between 100nm and 1000 nm) of the two parallel Py nanoelectrodes of 15-100 μ m length ensure subsequent switching in increasing magnetic fields. A suppression of spin polarized current is expected for antiparallel magnetization configuration of source and drain contacts (i.e. positive magnetoresistance) if spin injection and detection have been successfully implemented. Spin-valve devices are fabricated on thermally grown SiO₂ barriers of 1-2 nm thickness. Large-area bond contacts are isolated by a thick field oxide. The nanostructures are prepared by electron-beam lithography, electron-beam evaporation and subsequent lift-off. Magnetic force microscopy images at room temperature (RT) indicate single domain states of the Py nanowires in remanence. Reducing the nanowire width increases the coercive fields (up to 40 mT) of the magnetic hysteresis curves of Py nanowire arrays measured at temperatures from 5 K up to 300 K as required for device operation. The electrical properties of the contacts are characterized at 4.2 K and 300 K. Positive magnetoresistance (MR) effects are measured at 4.2 K as expected for spin-valve operation contrary to the negative anisotropic MR measured for single Py wires. We discuss the observed MR of the spin-valve element in terms of spin blockade and of classical Lorentz resistance of the semiconductor.

SESSION P4: FROM MAGNETORESISTANCE TO

QUANTUM COMPUTING

Chair: Hiro Munekata

Tuesday Afternoon, December 3, 2002

Room 204 (Hynes)

1:30 PM *P4.1
MAGNETORESISTIVE SWITCH EFFECT IN METAL/ SEMICONDUCTOR HYBRID STRUCTURES. Hiro Akinaga, SYNAP-AIST, Tsukuba, JAPAN.

In this contribution, a huge positive magnetoresistance (MR) effect, which was discovered in metal / semiconductor hybrid structures, and the recent progress of the research toward the magnetic-field sensor application are shown. The structure consisting of nanoscale metal-islands that are grown on a semi-insulating GaAs substrate by molecular-beam epitaxy exhibits magnetic-field-sensitive current-voltage characteristics. When constant voltage, above the threshold value, is applied to the film, very steep change in the current, which we term magnetoresistive switch, appears under a low magnetic field even at room temperature. The switch yields the huge MR effect, as high as 450%, 2200%, 9000% at magnetic fields of 30, 500, 1000 Oe, respectively. Among potential materials for the metal-islands, it was found that Au, Al and MnSb all worked well. The origin of the magnetoresistive switch effect is discussed in terms of a novel concept of magnetic-field sensitive avalanche breakdown. The magnetic-field sensitivity and the response time of the effect are decisive parameters for the sensor application. Recent experimental results indicated the close relation of these parameters to the morphological condition of metallic nano-structures and the electronic properties of the metal-/semiconductor-interface. This work was performed in SYNAP-AIST with M. Mizuguchi, H. Oki, T. Manago, under the joint research agreement with K. Ono, M. Oshima, K. Uchida, N. Miura (Univ. Tokyo) H. Oshima (Fujitsu Ltd.), and partly supported by the New Energy and Industrial Technology Development Organization (NEDO).

2:00 PM **P4.2**
Abstract Withdrawn.

2:15 PM P4.3
SPIN POLARIZED TUNNELING IN DELTA DOPED RESONANT TUNNELING DEVICES. Derek A. Stewart, Sandia National Laboratories, Livermore, CA; Mark van Schilfgaarde, Arizona State University, Dept of Materials, Tempe, AZ.

Magnetic resonant tunneling devices offer one approach to the development of a near ideal spin valve with high magnetoresistance. Resonant enhancement of magnetoresistance for certain device geometries may be exponentially large. These devices offer potentially high TMR values in combination with industrially relevant current densities. The ability to grow these devices using semiconductor fabrication techniques also provides a distinct advantage over current GMR devices. While several studies have concentrated on the role of dilute magnetic semiconductor leads, incorporation of digitally doped magnetic layers also holds promise for spin valve devices. Using an ab-initio principal layer Green function technique developed in the LMTO framework, we examine transmission through a series of double barrier GaAs|AlAs|GaAs|AlAs|GaAs resonant tunneling devices (RTDs) digitally doped with Mn or Cr in the layers outside the barriers. Calculations are also performed for nonmagnetic GaAs—AlAs RTDs with similar dimensions for comparison. Due to significant charge transfer at the heterostructure interfaces, self consistent calculations using a linear response technique are performed in all cases. The role of d band states near the Fermi energy in promoting spin polarized transmission is explored. In each case, the magnetic dopants lead to splitting of the transmission peaks in both the valence and conduction bands. Suppression of transmission in the minority spin channel is also observed as valence quantum well states move closer to the Fermi energy level. Adjustment of the quantum well width can lead to almost complete resonant transmission (97%) in one spin channel for ferromagnetically aligned Mn doped layers. Preliminary zero bias conductance calculations determined TMR values in excess of 1,000%. While spin flip events due to spin-orbit coupling, magnon scattering and imperfect interfaces will act to reduce this predicted TMR, it should still be significant.

2:30 PM P4.4
MAGNETIC FIELD DEPENDENT DIELECTRIC CONSTANT IN SeCuO_3 . G. Lawes, Los Alamos National Laboratory, Los Alamos, NM; M.A. Subramanian, DuPont Central Research and Development, Experimental Station, Wilmington, DE; A.P. Ramirez, Los Alamos National Laboratory, Los Alamos, NM.

Materials demonstrating strong magnetoelectric coupling between spin and charge degrees of freedom promote the development of novel composite devices. We have investigated one such compound SeCuO_3 , an insulating ferromagnet below 25K, by examining the dielectric behavior in the presence of a magnetic field. We find that the temperature dependent dielectric constant drops sharply at the magnetic ordering transition, and that it is very sensitive to an external magnetic field below this temperature. We attribute this behavior in part to an interplay between magnetic domain walls and electric polarizability. Among other applications, this intrinsic materials property can be used to capacitively measure small magnetic fields.

3:15 PM P4.5
MANIPULATION OF FREE 2D ELECTRON SPINS IN Si BY PULSED ESR. Alexei Tyryshkin, S.A. Lyon, Princeton Univ, Electrical Engineering Department, Princeton, NJ; W. Jantsch, F. Schäffer, Institut für Halbleiter- und Festkörperphysik, Univ of Linz, Linz, AUSTRIA.

Electrons in silicon are prime candidates for spintronics and quantum information processing applications, because silicon's weak spin-orbit interaction is expected to give long electron spin lifetimes. Using pulsed electron-spin-resonance (ESR) we have demonstrated the direct manipulation of the spin of free conduction electrons in Si quantum wells. Previous cw-ESR experiments on samples of this variety have found a narrow resonance associated with the 2-dimensional (2D) electron system. In the pulsed-ESR experiment, we find that the spin lifetime (T_1) and phase memory time (T_2) are both several microseconds. These times are 2 orders of magnitude longer than the length of the microwave pulses we use to flip the spins, directly demonstrating that many coherent spin operations are possible. The samples consist of a 200 Å thick, one-side modulation-doped Si quantum well grown on a relaxed SiGe buffer. Persistent photoconductivity is used to introduce electrons into the quantum well and control their density. Structures from the same wafer have shown Hall mobilities of $>10^5 \text{ cm}^2/\text{Vs}$ at LHe temperature. The ESR experiments were conducted with the 2D layer oriented perpendicular to the external magnetic field, and at a

microwave frequency of approximately 9.8 GHz. Inversion-recovery ($\pi-\tau-\pi/2$) and 2-pulse echo ($\pi/2-\tau-\pi-\tau$ -echo) sequences were used to measure T_1 and T_2 , respectively. The decays are not purely exponential indicating a distribution of relaxation times. The longest times were obtained with the samples cooled in the dark, illuminated at LHe temperature, and then briefly warmed to about 30K. The relaxation times we obtained are as long as $T_1 = 2.3 \text{ msec}$ and $T_2 = 3.0 \text{ msec}$. While similar to one another, in all cases we find that $T_2 > T_1$. T_2 exceeding T_1 is unusual and is indicative of a strongly anisotropic relaxation process. These results support the suggestion that an in-plane Rashba-field dominates the spin relaxation.

3:30 PM P4.6
RABI-BEAT ECHOES OF SPIN-DEPENDENT CHARGE CARRIER RECOMBINATION RATES. Christoph Boehme, Klaus Lips, Hahn-Meitner-Institut Berlin, Berlin, GERMANY.

Spin selection rules of charge carrier recombination transitions are known to be present in many semiconductor bulk and interface systems. In the study presented, it is shown, that a coherent manipulation of the spin state of electron-hole pairs trapped in localized band gap states of hydrogenated microcrystalline silicon is reflected in the transient behavior of the recombination rate and thus in a photocurrent applied to the material. The experiment used is coherent pulsed electrically detected magnetic resonance, a recently developed combination of pulsed electron spin resonance and electrically detected magnetic resonance. First experimental results show photocurrent transients whose dependency on the microwave pulse lengths, intensities and phase changes are indicative of rapidly dephasing spin Rabi-beat oscillations that take place within the ensemble of trapped charge carrier pairs. These coherently dephasing beat oscillations are rephasable and hence an echo effect in the recombination rate can be observed, a recombination echo. The experimental observation that coherent spin pair states of two charge carriers can govern recombination is discussed with regard to applications for readout mechanisms of nuclear-spin based solid state quantum computers.

3:45 PM P4.7
MATERIALS ENGINEERING TOWARDS REALIZATION OF AN ALL SILICON QUANTUM COMPUTER. T. Sekiguchi, Y. Matsumoto, and Kohei M. Itoh, Keio Univ, Dept Applied Physics and CREST-JST.

We have recently presented a novel scheme for a solid-state implementation of a quantum computer composed entirely of silicon. [quant-ph/0109039, Phys. Rev. Lett. in press.] Our naming, all silicon quantum computer, represents the fact that the scheme requires no doping or electrical contacts. However, it still demands for the advancement of the state-of-the-art materials technology. For example, qubits are nuclear spins ($I=1/2$) of ^{29}Si stable isotopes arranged as mono-atomic wires fabricated on a spin-free ^{28}Si stable isotope substrate. Therefore, it is important to develop a method to fabricate and characterize mono-atomic wires of silicon on silicon. Once qubits are formed, the nuclear spin resonant (NMR) frequency of each qubit is separated from others by a large and homogeneous field gradient arising from the micro-magnet placed monolithically on the ^{28}Si substrate. For this purpose, a few micron thick ferromagnetic film with a large, easy magnetization axis in the direction perpendicular to the substrate needs to be formed, and reactive-ion-etched (RIE) subsequently to realize an array of rod-shaped micro-magnets. The present paper reports the progress at Keio University towards realization of such materials engineering utilizing solid-source MBE and STM for the Si wire fabrication, and sputtering and RIE for micro-magnet fabrication.

4:00 PM P4.8
INVESTIGATION OF SPIN LIFETIMES IN N-TYPE GALLIUM ARSENIDE FOR FREE BAND ELECTRON SPINS AND DONOR SPINS ACROSS THE METAL-INSULATOR TRANSITION. Marcus Heidkamp, Aberrahmane Oulmquadem, Thomas Rohleder, Andreas Tillmanns, Bernd Beschoten, and Gernot Güntherodt, RWTH Aachen, 2. Physikalisches Institut, Aachen, GERMANY.

The observed spin lifetimes of optically pumped electron spins in n-doped GaAs which exceed 100ns [1] and the spin coherence lengths which are longer than $100\mu\text{m}$ [2] at low temperatures are promising for the development of potential spintronic devices. The fundamental physical processes responsible for these long lifetimes still remain not well understood. To identify the relevant electronic states for spin coherence and to better understand the underlying spin dephasing mechanisms we performed time-resolved magneto-optical Kerr spectroscopy on Si doped GaAs for donor concentrations ranging from $4 \times 10^{15} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$. By varying the photon energy both free band electron spins at higher energies and donor spins at lower energies can be optically excited. Over a temperature range from 5 to 300K a separation of both contributions is feasible according to their

distinct spin lifetimes, electron g-factors, and doping concentration across the metal-insulator transition. Using resonant spin amplification as first used in [1], we can assign the longest spin lifetimes of more than 100ns to the donor-related electronic states, which also show the strongest *B*-field dependence. On the other hand, free band electron spins have significantly shorter spin lifetimes of around 20ns depending less on magnetic fields. Based on these results spin dephasing mechanisms of both components can be analyzed independently. This analysis indicates a spin dephasing mechanism for the donor related electron spins that depends on the carrier localization length. *Supported by BMBF FKZ 01BM160 and 13N8244.* [1] J.M. Kikkawa and D.D. Awschalom, *Phys. Rev. Lett.* **80** (19), 4313 (1998). [2] J.M. Kikkawa and D.D. Awschalom, *Nature* **397**, 139 (1999).

4:15 PM P4.9

G-FACTOR ENGINEERING OF InGaAs/InP HETERO-STRUCTURES. Edward T. Croke, Andrew T. Hunter, Bin Shi, HRL Laboratories, LLC, Malibu, CA; Robert N. Schwartz, Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, CA.

A significant amount of research is currently being devoted to the physical implementation of quantum information processing devices. Of particular interest is the design of solid state devices for storing and manipulating quantum information utilizing the electronic spin degree of freedom of the carriers in semiconductors. Our research effort has focused on the design and fabrication of an entanglement-preserving photo-detector in which the quantum information is initially encoded in the photons polarization, and then transferred to the electronic spin system in an InGaAs/InP heterostructure. In order to construct such a device the photo-detector must absorb equally in the two spin states $|+\rangle$ and $|-\rangle$. This requires electronic g-factor engineering of the III-V semiconductor alloy. For measuring the g-factors of tailored materials we have constructed an electrically detected electron paramagnetic resonance (EDEPR) spectrometer operating at 30 GHz and capable of measurements down to temperatures below 1 K. We will present g-factor data on tailored materials based on the InGaAs/InP system. The effects of strain, alloy concentration, and quantum confinement on the g-factor will be discussed. This work was supported by the Defense Advanced Research Projects Agency and the Army Research Office under Contract Number DAAD19-01-C-0077.

4:30 PM P4.10

TRANSPORT SIMULATION OF PRECESSING SPIN DISTRIBUTION ACROSS SEMICONDUCTOR HETERO-JUNCTIONS. Paul von Allmen and Gerhard Klimeck, NASA, Jet Propulsion Lab, California Institute of Technology, Pasadena, CA.

Magneto-optic experiments have recently investigated the transport of precessing spin distributions across a semiconductor heterojunction. It was found that a spin polarized electron distribution efficiently diffuses from a GaAs substrate to a ZnSe epilayer [1]. Time resolved Faraday rotation measurements have shown that the dynamics of electrons accumulated in the epilayer is determined by the ZnSe Landé factor and spin relaxation time. Later measurements have shown that the spin dynamics changes from ZnSe to GaAs in nature if a potential drop is applied between the epilayer and the substrate [2]. We will present numerical results that reproduce these experimental data and show that the shift in spin dynamics is determined by the relative time scales of spin diffusion and Larmor precession. Two approaches will be examined. In the first approach, we solve the continuity equation for spin accumulation as was used for the study of the spin momentum transfer mechanism [3]. The second model relies on the non-equilibrium Greens function formalism to describe the coupled dynamics of spin diffusion and electron thermalization. Both approaches lead to numerical results in excellent agreement with experiments.

- [1] I. Malajovich, J.M. Kikkawa, D.D. Awschalom, J.J. Berry and N. Samarth, *Phys. Rev. Lett.* **84**, 1015 (2000)
- [2] I. Malajovich, J.J. Berry, N. Samarth and D.D. Awschalom, *Nature* **411**, 770 (2001)
- [3] M.D. Stiles and A. Zangwill, preprint (2002)

4:45 PM P4.11

OPTICAL ORIENTATION AND FEMTOSECOND SPECTROSCOPY OF SPIN POLARIZED HOLES IN GALLIUM ARSENIDE. D.J. Hilton and C.L. Tang, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

Optical orientation of spin polarized heavy and light holes followed by relaxation to other valence subband states has been observed unambiguously in undoped bulk GaAs. The spin relaxation time for the heavy holes is approximately 110 fs.

SESSION P5: POSTER SESSION SPINTRONIC MATERIALS AND APPLICATIONS

Chair: John Y.T. Wei
Tuesday Evening, December 3, 2002.
8:00 PM
Exhibition Hall D (Hynes)

P5.1

PLD GROWTH OF NOVEL MAGNETIC SEMICONDUCTOR Cr-DOPED ZnO AND ITS OPTO-SPINTRONIC PROPERTIES. Issei Satoh, Takeshi Kobayashi, Takanori Okada, Tadashi Itoh, Teruo Ono, Saburo Nasu, Dept of Physical Science, Grad Sch of Engineering Science, Osaka Univ, Osaka, JAPAN.

To realize opto-spintronic devices, it is strongly requested that the semiconducting materials should have the magnetism with high Curie temperature (T_C) as well as the excellent optical (luminescence) properties. In the present work, the magnetic and optical properties of novel magnetic semiconductor Cr-doped ZnO were examined. All Cr-doped ZnO thin films were grown on ZnO (0001) and Al_2O_3 (0001) substrates by the Ar-F excimer laser ablation (pulsed laser deposition; PLD) method. For PLD growth of Cr-doped ZnO films, an Ar-F ($\lambda = 193$ nm, 10 ns) excimer laser (laser fluence 1-3 J/cm² shot, repetition rate 1-10 Hz) and Cr_2O_3 mixed ZnO ceramic bulk target were used. All conductive Cr-doped ZnO films indicated ferromagnetic signature. Whereas, there was no sign of ferromagnetism in any non-conductive films. The carrier-induced ferromagnetism seems to be responsible for the observed conductivity dependence of the magnetic properties. To know the optical properties and to obtain more direct indication of "the carrier-induced ferromagnetism" in Cr-doped ZnO, we did the photoluminescence (PL) measurements. The first result is the intensive PL from Cr-doped ZnO at room temperature. The PL peaks (free and bound exciton) are very sharp and there is no deep level emission. The second one, to be emphasized, is the amazing modulation of PL intensity by the magnetic field application. It increased about 3 times with increasing magnetic field up to 1 T at 4.2 K, and peak wavelength was slightly blue-shifted. Both the Zeeman split of the exciton level and strong carrier-spin correlation might well account for the observed PL properties.

P5.2

MAGNETISM IN (Ga,Cr)As. A. Dakhamra, B. Lakshmi, D. Heiman, Northeastern Univ, Dept of Physics, Boston, MA.

Magnetic, transport, and structural studies were carried out on $\text{Ga}_{1-x}\text{Cr}_x\text{As}$, $x=0.1$ to 0.3, grown by low temperature MBE. The magnetic properties were investigated using a SQUID magnetometer in magnetic fields up to $B=5$ T and temperatures $T=3$ to 300 K. Two regimes of magnetism were found: ferromagnetism (FM) at low- x , changing to paramagnetism at higher- x . The magnetization in the FM phase saturates in magnetic fields $B=1$ T at low temperatures. The saturation magnetization decreases for increasing temperature, pointing to a FM transition temperature of $T_c \approx 30$ K. Annealing of the FM samples results in decreased interaction. Magnetotransport measurements yield a room temperature resistivity of $\rho=0.1$ Ωcm and a carrier concentration of 10^{21} cm^{-3} . The high carrier concentration indicates that Cr also acts as an acceptor similar to shallower Mn. For decreasing temperature the resistivity increased rapidly as the itinerant carrier concentration decreases due to Anderson localization. The samples became strongly insulating at low temperatures, even in the FM state. In x-ray scans the zincblende structure predominates for $x=0.1$ and exhibits a larger lattice constant than for $x=0$ GaAs. Finally, the field dependence of the low temperature magnetization, $M(B)$, displays a complex behavior which was analyzed in the framework of both large scale FM domains and microscopic domains (magnetic polarons).

P5.3

CROSS-SECTIONAL STM AT THE EDGE: CHARACTERIZING SPINTRONIC HETEROSTRUCTURE INTERFACES. G.I. Boishin^t, A.T. Hanbicki, B.T. Jonker, and L.J. Whitman, Naval Research Laboratory, Washington, DC. ^t(An employee of Nova Research, Inc., Alexandria, VA.)

The performance of semiconductor "spintronic" devices is highly dependent on the quality of the epitaxial films and heterointerfaces because of their critical roles in spin-polarized carrier injection, transport, manipulation, and detection. Cross-sectional scanning tunneling microscopy (XSTM) is a powerful technique for characterizing III-V(001) semiconductor films and interfaces, whereby the structure can be observed atom-by-atom across an single $\{110\}$ cleavage plane through a device. Most spintronic devices consist of heterostructures combining materials with very different electrical and physical properties, such as $\text{ZnMnSe}/\text{AlGaAs}$ or Fe/AlGaAs . Moreover, the films and interfaces of interest are often single structures located within a few nanometers of the cross-sectional edge. These characteristics pose significant challenges to the application of XSTM; for example, obtaining an atomically-flat cleavage surface,

finding the isolated interface of interest at the sample edge while maintaining stable imaging conditions, and scanning over materials with widely varying band gaps and band alignments. We will discuss the approach we have taken to successfully cleave such challenging samples, and how we find and characterize the interfaces of interest. Results from a variety of spintronic devices will be shown, including XSTM images of a single GaAs quantum well, a ZnSe heteroepitaxial film and ZnMnSe/AlGaAs interface, and the first successful XSTM observation of an Fe/AlGaAs interface. Supported by ONR and DARPA-DSO.

P5.4

THE ELECTRONIC STRUCTURE OF RARE EARTH PNICTIDES
ErAs. Takashi Komesu, Jaewu Choi, C.N. Borca, Hae-Kyung Jeong, P.A. Dowben, University of Nebraska-Lincoln, Dept. of Physics and Astronomy, Lincoln, NE; Andre Petukhov, South Dakota School of Mines and Technology, Rapid City, SD; B.D. Schultz, and C.J. Palmström, University of Minnesota, Dept. of Chemical Engineering and Material Science, Minneapolis, MN.

Erbium arsenide (ErAs) is one of a class of rare-earth pnictides that have been a subject of much discussion regarding the band structure [1] because of the "coupled" magnetic and electronic properties. These rare earth compounds, as magnetic materials, are dominated by the strong exchange coupling between the relatively large local moments of 4f and valence electrons mediated by the conduction electrons near the Fermi level (E_F). The exchange splitting near E_F is calculated to be in the vicinity of 160 meV, but is strongly dependent upon wave vector while the theoretical band calculations suggest only a "shallow" crossing of E_F from the unoccupied bands increasing wave vector value [1]. The experimental band structure of ErAs(100), grown epitaxially on GaAs(100), has been mapped out using photoelectron spectroscopy (PES) and inverse photoemission spectroscopy (IPES). The combination of PES and IPES shows significant indications of the E_F crossing of two bands. The electronic structure is dominated by bulk bands qualitatively consistent with the calculated band structure, though a number of additional non-dispersing multiplet levels can be identified in the valence band structure. From symmetry selection rules, photoemission provides strong evidence that the Δ_5 (or e) symmetry bands are a consequence of hybridization between Er and As, while the Δ_1 (or a_1) symmetry bands have strong contributions from Er-Er and/or As-As hybridization, and possible contributions from nonbonding or antibonding states between Er and As. It is now apparent that the magnetic and electronic structure of these 4f local moment systems cannot be studied by a single experimental technique. Rather, the two complementary techniques of photoelectron spectroscopy (PES) and inverse photoemission spectroscopy (IPES) are necessary for a comprehensive investigation of the surface electronic structure. [1] A.G. Petukhov, W.R.L. Lambrecht and B. Segall. Phys. Rev. B 53, 4324 (1996).

P5.5

SINGLE CRYSTALS OF DILUTE MAGNETIC SEMICONDUCTORS: GROWTH AND CHARACTERIZATION. B.C. Sales, D. Mandrus, R. Jin, J.R. Thompson, L.A. Boatner, J.O. Ramey, H.A. Mook Jr., Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN.

One of the surprises encountered in the fabrication of thin films of various dilute magnetic semiconductors (DMS) was the observation by several different research groups of carrier-mediated ferromagnetism at remarkably high temperatures (100-600 K). The origin and detailed nature of the ferromagnetism in DMS is controversial. Neutron scattering is the premier technique in the study of magnetism. To make use of the full power of neutron scattering, however, requires relatively large single crystals (0.1-2 cm³). We have grown single crystals of several different DMS and will report on our initial investigations of these interesting materials. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U. S. Department of Energy under contract DE-AC05-00OR22725.

P5.6

FERROMAGNETISM ABOVE ROOM TEMPERATURE IN AlMnAs-CLUSTER STRUCTURES GROWN BY METAL ORGANIC VAPOUR PHASE EPITAXY. Michael Lampalzer, Kerstin Voiz, Werner Treutmann, Siegfried Nau, Torsten Torunski, Wolfgang Stolz, Philipps-University Marburg, Materials Sciences Center, Marburg, GERMANY.

In the recent years the interest on diluted magnetic III/V-semiconductors as a basis for spin-(opto-) electronics has been increased. Especially, materials like (GaMn)As and (InMn)As have been investigated. Here, we present our studies of the novel material ferromagnetic (AlMn)As-clusters grown by MOVPE. For high Mn-concentrations in combination with growth temperatures in the range of 600°C, we achieve (AlMn)As-clusters embedded in a surrounding AlAs:Mn matrix. The (AlMn)As clusters show

ferromagnetism with a Curie temperature of 320 K. All the samples have been grown in a standard commercial horizontal MOVPE reactor system (AIX 200, Aixtron Corp.) The structural properties of the layers are investigated by atomic force microscopy (AFM) and high-resolution X-ray diffraction (XRD). The composition of the clusters is determined by nanoscale energy-dispersive X-ray (EDX) element analysis in a transmission electron microscope (TEM), the magnetization via SQUID-magnetometer. The embedding of the clusters in the matrix is investigated by TEM. In addition, electrical properties of the Mn-doping are measured by (temperature dependant) Hall studies. For selected growth conditions, the studies are extended on (AlGaMn)As-structures as well. These properties of the (AlGaMn)As-cluster layers are compared to the MOVPE-growth in the (GaMn)As material system, where Mn(Ga)As-clusters are defect-free embedded in the surrounding matrix. There, AlAs is employed as a suitable overgrowth material for cluster structures. Al diffuses into the Mn(Ga)As clusters during the overgrowth process. The differences in the magnetic properties as a function of Al-content in the clusters, and in particular the in-plane magnetic anisotropy of these materials, are investigated by SQUID-magnetometer measurements. The ferromagnetism above room temperature and the perfect embedding in the surrounding matrix gives a new degree of freedom for the use of Mn-cluster containing III/V-materials in future multilayer structures designed for spin-(opto-)electronics.

P5.7

A KEY TO ROOM TEMPERATURE FERROMAGNETISM IN Fe-DOPED ZnO:Cu. S.-J. Han, J.W. Song, C.-H. Yang, S.H. Park, J.-H. Park, Y.H. Jeong, Pohang Univ of Science and Technology, Dept of Physics and eSSC, Pohang, S. KOREA.

Successful synthesis of room temperature ferromagnetic semiconductors, $Zn_{1-x}Fe_xO$, is reported. The essential ingredient in achieving room temperature ferromagnetism in bulk $Zn_{1-x}Fe_xO$ was found to be additional Cu doping. A transition temperature as high as 550 K was obtained in $Zn_{0.94}Fe_{0.02}Cu_{0.01}O$; the saturation magnetization at room temperature reached a value of $0.75 \mu_B$ per Fe. Large magnetoresistance was also observed below 100 K.

P5.8

BREAKDOWN OF Al / AlO / Al TUNNELING JUNCTIONS. Takeshi Morozumi, Hideo Kaiju, Shigeo Fujita, Shiiki Kazuo, Keio Univ, Dept of Applied Physics and Physico-Informatics, Yokohama, JAPAN.

One of the problems of tunneling junctions is breakdown of an insulating layer. The breakdown mechanism of Al / AlO / Al tunneling junctions is studied. Al (10 nm) / AlO (1.5 - 5 nm) / Al (50 nm) tunneling junctions were fabricated onto a glass substrate by ion-beam mask sputtering. The AlO thin film was formed by oxidation of Al layer in pure O₂ gas for about 20 hours. The barrier height and thickness of AlO thin film were evaluated from fitting current-voltage characteristics to the Simmons equation. The breakdown was measured by a dc four-probe method at temperatures between 300 and 400 K. Impedance was measured by an ac two-probe method in the frequency range from 0 to 110 MHz. The breakdown electric field increases as the barrier thickness decreases. It reaches 4×10^8 V/m for the junction with barrier height of 1.4 eV and thickness of 1.5 nm, which is much larger than 1×10^7 V/m for the bulk. The breakdown electric field is found to decrease as the barrier height decreases. The temperature dependence of the current density $i(T)$ is proportional to T^2 for junctions with barrier height more than 0.7 eV, which agrees to the Stratton's theory. The high-frequency impedance characteristics of these junctions can be explained by the parallel circuit of resistance and capacitance. The results imply that the junctions do not have leak current. However, the current $i(T)$ is proportional to $\exp(T^2)$ for junctions with low barrier height of about 0.2 eV. The high-frequency impedance characteristics were expressed as the parallel circuit of tunneling resistance, capacitance and inductance. The leak current ratio is found to increase as the barrier height decreases. The breakdown is accelerated by the leak current.

P5.9

HIGH-FREQUENCY DIELECTRIC CONSTANT CHARACTERISTICS OF SPIN TUNNELING JUNCTIONS. Hideo Kaiju, Naoki Hirabayashi, Takeshi Morozumi, Shigeo Fujita, Kazuo Shiiki, Keio Univ, Dept of Applied Physics and Physico-Informatics, Yokohama, JAPAN.

The dielectric constant characteristics of spin tunneling junctions (STJs), in which two ferromagnetic metal layers are separated by a thin insulating layer, have not been clarified in the high-frequency range. In the present study, the high-frequency dielectric constant characteristics of the STJs are investigated. Coercive differential STJs Al (500 nm) / Co (10 nm) / AlO_x (1.3 nm) / Co (50 nm) / Al (488 nm) were fabricated on glass substrates by ion-beam mask sputtering. The sputtered Al film was oxidized in pure O₂ gas for 12-24 hours.

The dielectric constant was measured by a four-probe method and a two-probe method at room temperature in the frequency range from 120 to 100 MHz. The junction area was measured by the scanning laser microscope. The AlO_x barrier thickness, evaluated from a fit to the Simmons equation, was in good agreement with results obtained from angle-resolved X-ray photoelectron spectroscopy. The effective dielectric constant of junctions with the high barrier over 0.46 eV is approximately equal to the dielectric constant of bulk Al_2O_3 , $7.12 \times 10^{-11} \text{ Fm}^{-1}$, which seems to be independent of the frequency or slightly decrease in the high-frequency range. The effective dielectric constant of junctions with the low barrier of less than 0.38 eV is found to decrease sharply in the high-frequency range over 1 MHz. These experimental results for junctions with the low barrier can be explained by calculated model of $(R_t, R_c, L_c) || (C_t, R_c, L_c)$ equivalent circuit, where R_t , C_t , R_c , and L_c are the tunneling resistance, capacitance, conduction resistance, and conduction inductance, respectively. This indicates that conduction atoms, such as unoxidized Al and Co, are remained in the AlO_x insulating region for junctions with the low barrier.

P5.10

Abstract Withdrawn.

P5.11

SPIN RELAXATION AND DEPHASING IN A GaAs QUANTUM WELL. Vadim I. Fuller, Lev G. Mourokh, Norman J.M. Horing, Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, NJ; Anatoly Yu. Smirnov, D-Wave Systems Inc., Vancouver, BC, CANADA.

We examine electron spin relaxation/dephasing in a GaAs quantum well, in a normal magnetic field. We consider D'yakonov-Perel' spin-orbit interaction as the principal source of electron spin relaxation/dephasing (which is typical for non-centrosymmetric semiconductors at moderate temperatures). The theoretical analysis was divided into two distinct stages based on the relaxation time hierarchy: (i) spin relaxation/dephasing due to electron spin interaction with the orbital degrees of freedom, and (ii) thermalization of electron velocity in the presence of a magnetic field due to electron-phonon/impurity interactions. In the first stage (i), we considered the orbital motion of the electron as an effective heat bath, which can be characterized by the correlation and response functions of its variables. We derived a set of standard Bloch equations, with the relaxation (longitudinal) time, T_1 , and dephasing (transverse) time, T_2 , defined by (for $<100>$ orientation of the well): $T_1 = T_2/2 = \tau_s/2$, with $\tau_s^{-1} = 2\lambda^2 \hbar^{-2} K (\omega_B) [(\omega_B - \omega_c)^2 + \gamma_0^2]^{-1}$, where λ is the spin-orbit coupling constant and $\omega_B = geB/2mc$ is the spin precession frequency, whereas $\omega_c = eB/mc$ is the cyclotron frequency. γ_0 is the velocity relaxation rate and $K(\omega)$ is the spectrum of velocity fluctuation sources, both of which we determine microscopically (in terms of the coupling constants and structure parameters) from the interaction of orbital motion with phonons/impurities. Our results reveal new information concerning the dependences of the spin relaxation and dephasing times, T_1 , T_2 , on magnetic field and temperature.

P5.12

QUANTUM CONFINEMENT EFFECTS ON SPIN WAVES IN A FERROMAGNETIC FILM. E. Hernan Vivas C., Juan Carlos Granada E., Universidad del Valle, Departamento de Fisica, Santiago de Cali, COLOMBIA.

A formalism is established in order to obtain the complete magnetic susceptibility tensor components $\chi_{ij}(\mathbf{k}; \omega)$ attached to the ferromagnetic thin film, for both exchange-dipole interaction and high confinement ($L \approx \lambda$) regime. Special attention is given to the resonant and non-resonant electromagnetic-surface spin wave coupled modes at the short wavelength approximation; taking into consideration the radio frequency magnetic fields polarization (h^{rf}) propagating in a parallel-to-plane as well as the out-plane film direction. The number of thermal spin-flip active modes is calculated using numerical integration on the 2D density state functional, joined with Boltzmann's statistical factor. It is found a critical confinement parameter L_C which determines not only the collective excitations stability but also the scale-change dependence with different applied magnetic field intensities.

P5.13

LOW-FIELD TRANSVERSE MAGNETOVOLTAGE IN MANGANITE FILMS. V. Moshnyaga, S.A. Köster and K. Samwer, I. Physikalisches Institut, Universität Göttingen, GERMANY.

The temperature and magnetic field dependence of the transverse voltage, V_y , were studied in patterned epitaxial films of $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3/\text{MgO}$ with $T_C=270$ K and $\text{La}_{0.7}(\text{Ca},\text{Sr})_{0.3}\text{MnO}_3/\text{MgO}$ ($T_C=310$ K). At $T > T_C$ the $V_y(T)$ shows

an insulating behavior similar to that of the longitudinal voltage, $V_x(T)$, (resistance). As the long range ferromagnetic order sets in for $T \sim T_C$ an additional contribution to V_y appears. The field dependence, $V_y(H)$, is extremely sharp in the vicinity of the coercive field and shows a hysteretic behavior due to the magnetization reversal. The corresponding signal changes 20 %/Oe or 50 $\mu\text{V}/\text{Oe}$ for very low fields $H_c=10-20$ Oe at room temperature. The transverse voltage is discussed as an anisotropic magnetoresistance (AMR) effect and reaches its maximum in the vicinity of T_C for low magnetic fields $H \sim 50$ Oe. The results show a potential of manganite based transverse AMR microstructures for application in field sensing devices and memory elements even at room temperature. Support by the DFG via SFB602, TPA2 is acknowledged.

P5.14

CURIE TEMPERATURES OF MAGNETICALLY HEAVILY DOPED III-V/Mn ALLOYS. S. Souma^a, S.J. Lee^{a,*}, N. Kim^{a,b}, T.W. Kang^a; ^aDongguk University, Quantum-Functional Semiconductor Research Center, Seoul, KOREA; ^bDept. of Physics, University at Buffalo, Buffalo, NY.

Curie temperatures of III-V/Mn alloys are calculated taking into account the formation of ferromagnetic clusters, the percolation picture of phase transition, and the introduction of locally much higher local Mn ion concentrations compared with DMS. The result shows that above-room-temperature ferromagnetism is possible in GaAs/Mn case, when the average inter-spin distance is 0.45nm T_c becomes 400K and comparison with other materials are given.

P5.15

INVESTIGATIONS ON CO-DOPED TiO_2 THIN FILMS PREPARED BY SPRAY PYROLYSIS. A. Manivannan, Department of Physics, West Virginia University, Morgantown, WV; S.B. Majumder, P.S. Dabal and R.S. Katiyar, Department of Physics, University of Puerto Rico, San Juan, PR.

Recently, there has been increased interest on the study of transition metal doped TiO_2 thin films for their potential applications in spintronics. Several research groups have prepared Co doped TiO_2 thin films using rf sputtering, MBE, and laser ablation techniques. We have prepared pure and Co-doped anatase TiO_2 films on ITO, FTO and glass substrates by spray pyrolysis. The properties of our Co doped TiO_2 films have been compared with the previous results. Optical absorption, X-ray diffraction, Raman and magnetic measurements have been carried out. X-ray diffraction studies showed that the (101) peak intensity for anatase phase of the film decreases significantly with increasing Co concentration as well as it shifts to the lower diffraction angle indicating an increase in the lattice parameter. Raman spectra also confirmed the anatase phase of the films. The lowest frequency E_g mode at 144 cm^{-1} exhibited a systematic down shift with increasing Co contents. The absorption edge of these films were measured using UV VIS spectrometry. The shift of band edge indicates the inclusion of Co ions in the TiO_2 lattice and thus supports the X-ray and Raman results. Magnetic measurements indicated ferromagnetic-like behavior for a 10% Co doped film. Details of our investigations with different Co concentrations will be presented.

P5.16

ADVANTAGE OF NITROGEN-RICH GROWTH FOR INCORPORATION OF MANGANESE INTO GaN USING RF PLASMA MOLECULAR BEAM EPITAXY. Costel Constantin, Muhammad Haider, Hamsad Al-Brithen, and Arthur R. Smith, Ohio University, Dept. of Physics and Astronomy, Athens, OH.

MnGaN is of great interest as a magnetic semiconductor for use in room temperature spintronic applications.¹ We investigated the incorporation of Mn in GaN, in the case of RF-plasma molecular beam epitaxy (MBE) using effusion cells for Ga and Mn and N_2 as the source of nitrogen. The Ga/N ratio was varied from 0.53 (N-rich) to 1.32 (Ga-rich) while the N-flux was kept constant. The Mn/Ga flux ratio was varied between 0 and 0.167. Samples were grown at substrate temperatures ranging from 500°C to 700°C in MOCVD grown GaN on sapphire substrates. The growth was monitored by reflection high-energy electron diffraction (RHEED). For Mn-Ga-N growth, the RHEED pattern shows a clear transition in going from N-rich to Ga-rich growth, similar to the behavior of GaN growth², namely spotty for N-rich and streaky for Ga-rich. However, while the streaky RHEED pattern suggests a smooth surface, scanning electron microscopy (SEM) reveals precipitation in the case of Mn-Ga-N in the form of lines and dots on the surface. For Mn/Ga flux ratio of 5.5%, these lines and dots have high Mn concentration (Mn/Ga peak area ratio up to 40%) as revealed by energy-dispersive x-ray (EDX), and no Mn is observed between these features. On the other hand, N-rich growth results in uniform Mn incorporation without precipitation as indicated by the absence of lines and dots. For Mn/Ga flux ratio of 6.8%, the Mn/Ga peak area ratio is 4.0%. This work is supported by

the National Science Foundation under Grant No. 9983816.

[1] T. Dietl *et al.* *Science* **287**, 1019, (2000).

[2] R.M. Feenstra *et al.* *Surf. Rev. Lett.* **7**, 601 (2000).

P5.17

FORMATION OF CO NANOCLOUDS IN EPITAXIAL

$Ti_{0.95}Co_{0.04}O_2$ THIN FILMS AND THEIR FERROMAGNETISM.
D.H. Kim, J.S. Yang, K.W. Lee, S.D. Bu, and T.W. Noh, ReCOE and School of Physics, Seoul National University, Seoul, KOREA; S.-J. Oh, CSCMR and School of Physics, Seoul National University, Seoul, KOREA; Y.-W. Kim, School of Materials Science and Engineering, Seoul National University, Seoul, KOREA; J.-S. Chung, Department of Physics, Soongsil University, Seoul, KOREA; H. Tanaka, H.Y. Lee, and T. Kawai, ISIR, Osaka University, Osaka, JAPAN.

Dilute magnetic semiconductor has become one of the most important topics in condensed matter physics recently. It is thought to be an essential element for a revolutionary type of devices called spintronics. We have investigated the ferromagnetism of newly discovered Co-doped TiO_2 films whose Curie temperature is well above the room temperature. Anatase $Ti_{0.95}Co_{0.04}O_2$ films were grown epitaxially on $SrTiO_3$ (001) substrates by using PLD with *in-situ* reflection high-energy electron diffraction. The oxygen partial pressure, P_{O_2} , during the growth was systematically varied. X-ray diffraction shows that the films grown epitaxially under the variations of the oxygen pressure. As P_{O_2} decreases, the growth behavior was changed from a 2-dimensional layer-by-layer like growth to a 3-dimensional island like one, which resulted in an increase in the saturation magnetization. These structural and magnetic changes were explained in terms of the formation of cobalt clusters, whose existence was proved by transmission electron microscope studies. Our work clearly indicates that the cobalt clustering will cause room temperature ferromagnetism in the Co: TiO_2 films.

P5.18

SWITCH PHENOMENA IN $La_{2/3}Mn_{1/3}O_3/Eu_2CuO_4/$
 $La_{2/3}Mn_{1/3}O_3$ RAMP-TYPE JUNCTIONS. W.H. Tang^{a,b}, T.L. Kam^a and J. Gao^b; ^aInstitute of Physics & Center for Condensed Matter Physics, Chinese Academy of Sciences, Beijing, CHINA; ^bDepartment of Physics, the University of Hong Kong, Hong Kong, CHINA.

$La_{2/3}Mn_{1/3}O_3$ (LCMO) is a well-known CMR material. The magnetic tunneling in CMR materials has attracted great interest in these years. In this work, ramp-type junctions of LCMO with Eu_2CuO_4 (ECO) were fabricated by rf-magnetron sputtering, photolithography and ion etching. A novel switch phenomenon was observed in the I-V curves below the Curie temperature (T_c) of LCMO electrodes. With increasing of voltage, the current cross the junction increases linearly first, then deviates its linearity, and then a sharp drop of current happened, and finally the current increases with the voltage linearly. The current drop happens at the same voltage of 209mV for different measuring temperatures, but the current drops starting different values. The starting current decreases with the increasing of temperature. The current drop disappears at about T_c . There is a hysteresis near the dropped point in the I-V curves when voltage increases and decreases. We cannot give a reasonable explanation about this abrupt drop now, but we believe that this abrupt drop could correspond one kind of switch phenomenon when LCMO changes from ferromagnetic metal into paramagnetic insulator.

P5.19

SPIN RELAXATION AND CARRIER TRANSPORT IN DIAMAGNETICALLY DILUTED PEROVSKITE MANGANITES. Natalia Noginova, Empress Arthur, George B. Loutts, Center for Materials Research, NSU, VA; Vadim A. Atsarkin, IRE, Moscow, RUSSIA.

To get information on the interplay of magnetic and lattice systems in manganese perovskites, electric carrier transport and nuclear spin-lattice relaxation have been studied in manganite single crystals of $LaGa_{1-x}Mn_xO_3$, with the concentration of Mn ions, x , varied from 0 to 100%. Temperature dependence of the spin-lattice relaxation rate reveals a thermally activated process with the characteristic energy of about 50 meV. The relaxation mechanism is attributed to dipole-dipole magnetic interaction of the Ga nuclei with the paramagnetic Mn^{3+} ions, their electron spin-lattice relaxation being governed by the thermally activated Jahn-Teller vibrations.

P5.20

ELECTRONIC STRUCTURE AND MAGNETISM IN MnN COMPOUNDS. Margarita Prikhodko and Walter R.L. Lambrecht, Case Western Reserve University, Cleveian, OH.

An electronic structure study of MnN compounds is presented. MnN has a slightly distorted rocksalt structure and if antiferromagnetic with the AFM-I or AFM_[001] ordering. Mn_3N_2 forms an ordered

vacancy compound of rocksalt with N vacancies every 3 (001) layers with the same AFM_[001] ordering. Full-potential linear muffin-tin orbital calculations were performed for MnN in the nonmagnetic, ferromagnetic, AFM-I and AFM-II AFM_[111] forms. The results indicate that the AFM-I state is below the FM state while the AFM-II state is above the FM state. This indicates exchange couplings $J_1 < 0$ and $J_2 > 0$ with $|J_2| > |J_1|$. This can be understood in terms of the double exchange mechanism via the intervening N. If we map this model on the classical Heisenberg Hamiltonian, we find that with such interactions, the model is frustrated. Several configurations have the same energy. The stabilization of the AFM-I ordering is presumably related to the slight c/a reduction. In Mn_3N_2 , we find a larger energy difference between AF and FM states with still the AF ordering having lower energy. An alternative AFM_[001] ordering has an energy slightly lower than the FM configuration. Further configurations are under study to extract the exchange interactions. The local densities of states provide insight in the formation of magnetic moments. The magnetic moments on the Mn atoms in planes without N are very close but slightly larger than those in planes with N, in agreement with experimental data.

P5.21

Abstract Withdrawn.

P5.22

EFFECT OF THE DIFFERENT HARD MAGNETIC LAYER ON THE RIGIDITY OF ARTIFICIAL ANTIFERROMAGNETIC SANDWICH IN SPIN VALVE STRUCTURES. Jianguo, Zhu, Dept of Materials Science, Sichuan University, Chengdu, P.R. CHINA; Zhenghong Qian, Nonvolatile Electronics, Inc, Eden Prairie, MN; Jack H. Judy, Dept of Electrical and Computer Engineering, University of Minnesota, MN.

In this paper, we report on the magnetic and transport properties of artificial antiferromagnetically (AAF) coupled NiFe/Ru/NiFe sandwiches, grown by RF sputtering on Si_3N_4/Si substrate. The AAF sandwiches are deposited on Buffer/Hard magnetic layer, and the magnetic and giant magnetoresistance loop were measured. It was found that the magnetic properties of the spin valve structure with AAF sandwiches were strongly influenced by the different hard magnetic layer. The rigidity of the spin valve with AAF sandwiches is improved when the $\alpha-Fe_2O_3$ was used as the hard magnetic layer. This gives rise to a sharp reversal of the magnetization vectors of the AAF, a flat magnetization and giant magnetoresistance plateau, which is very promising for spin electronic devices.

SESSION P6: FERROMAGNETIC SEMICONDUCTORS - I

Chair: Mark van Schilfgaarde
Wednesday Morning, December 4, 2002
Room 204 (Hynes)

8:30 AM *P6.1

SPIN-POLARIZATION AND ELECTRONIC STRUCTURE OF Mn CONTAINING DILUTE MANGETIC III-V SEMICONDUCTORS. James R. Chelikowsky, Leeor Kronik, and Manish Jain, University of Minnesota, Department of Chemical Engineering and Materials Science, Minneapolis, MN.

The systematic use of electron spin, in addition to its charge, holds great promise for a new class of semiconductor devices with unprecedented functionality. Recently, Mn-containing, "dilute magnetic", III-V semiconductors have emerged as candidate materials for such a technology. They can potentially produce charge carriers with well-defined spin, yet are compatible with already existing semiconductor technologies. In order to assess the performance limits of such materials theoretically, we present first principles pseudopotential - density functional calculations for the electronic structure of the dilute magnetic semiconductors $Mn_xGa_{1-x}N$, $Mn_xGa_{1-x}P$, and $Mn_xGa_{1-x}As$ with an experimentally relevant realistic $x=0.063$, in their ordered ferromagnetic phase. We predict that these materials allow, in principle, for a theoretical limit of 100% spin-injection, and that spin-polarized transport can be attained within the context of a simple band picture. We analyze band splitting and/or formation of impurity bands in the different materials and explain differences in term of the different orbital hybridization. We discuss the technological impact of these findings and compare our results to pertinent experimental data.

9:00 AM P6.2

PREPARATION AND PHYSICAL PROPERTIES OF (Ga,In,Mn)N EPILAYERS. T. Kondo, A. Oiwa, H. Owa and H. Munekata, Imaging Science and Engineering Laboratory, Tokyo Institute of Technology, Yokohama, JAPAN.

We report for the first time the epitaxy and physical properties of $(\text{Ga},\text{In},\text{Mn})\text{N}$. We expect the following two effects by the incorporation of indium into $(\text{Ga},\text{Mn})\text{N}$. Firstly, Mn may form a shallower acceptor level in the GaN host crystal. Secondary, incorporation of Mn may be enhanced by the reduction of formation energy due to the size compensation between In and Mn. If these expectations work as they do, carrier induced ferromagnetism at RT¹ can be realized in p -($\text{Ga},\text{In},\text{Mn})\text{N}$.

Samples were grown on sapphire(0001) substrates by using RF-plasma assisted MBE system. Epitaxy of $(\text{Ga},\text{Mn})\text{N}$ using this system is described elsewhere^{2,3}. The initial substrate nitridation was performed for 15 min at $T_s = 750^\circ\text{C}$ on thermally ($T_s = 900^\circ\text{C}$) cleaned substrates. This was followed by the growth of 5nm-AlN buffers and 200nm-GaN buffers. Finally, $(\text{Ga},\text{In},\text{Mn})\text{N}$ layers with Mn content of 1% were grown on top of the GaN layers at $T_s = 500\text{--}600^\circ\text{C}$. The Magnetization data show strong deviation from Brillouin type paramagnet; magnetization increases steeply at low magnetic field ($< 0.5\text{ T}$) and turn into a gradual change at higher field. Epilayers indicate n -type conduction that presumably arises from extrinsic donor states in GaN host crystal; carrier concentration and mobility, measured by van der Pauw method, are $3 \times 10^{19} \text{ cm}^{-3}$ and $1.4 \text{ cm}^2/\text{V}\cdot\text{sec}$ at RT, respectively. Negative magnetoresistance is clearly observed in the temperature range between 4.2 and 200K. The typical value of magnetoresistance $\Delta R/R$ at 4.2K is 5% with the applied magnetic field of 9T. This phenomenon may be originated from s-d exchange interaction between carrier and incorporated Mn ions.

References: ¹T. Ditel *et al.* *Science* **287**, 1019 (2000). ²S. Kuwabara *et al.* *Jpn. J. Appl. Phys.* **40**, L727 (2001). ³T. Kondo *et al.* *J. Crystal Growth* **237**–**239**, 1353 (2002).

9:15 AM *P6.3
IMPURITY BAND AND EFFECTIVE SPIN MODELS FOR THE MAGNETIC PROPERTIES OF DILUTED MAGNETIC SEMICONDUCTORS. R.N. Bhatt, Department of Electrical Engineering and Princeton Materials Institute, Princeton University, Princeton, NJ.

The discovery of ferromagnetism in III-V based diluted magnetic semiconductors potentially at temperatures of practical interest for spintronics, has given rise to several theoretical approaches to understand the magnetic properties of these materials, both at the microscopic, and phenomenological level. In this talk, I will review results of two main approaches - (a) a microscopic approach based on a simple impurity band description appropriate for low carrier densities, and (b) phenomenological effective spin approaches which have their roots in theories at high carrier densities. Properties discussed will include thermodynamic quantities such as specific heat, magnetization, magnetic susceptibility, and non-linear magnetic response. In addition, we will discuss the effect of positional disorder present in these alloy systems, on nature of electronic eigenstates, and of the low energy spin excitations, especially at low carrier densities, where the system is close to the metal-insulator transition. Work carried out in collaboration with Mona Berciu, Malcolm Kennett, Xin Wan and Chenggang Zhou.

9:45 AM P6.4
ALTERNATIVE DOPING STRATEGIES IN THE GaMnP SYSTEM. M.E. Overberg, G.T. Thaler, R.M. Frazier, S.J. Pearton, C.R. Abernathy, Dept of Materials Science and Engineering, University of Florida, Gainesville, FL; N. Theodoropoulou, A. Hebard, Dept of Physics, University of Florida, Gainesville, FL; R.G. Wilson, Stevenson Ranch, CA; J.M. Zavada, US Army Research Office, Research Triangle, NC.

Advances and refinement in materials preparation have produced interesting magnetic properties in a variety of semiconductors, oxides, and chalcogenides. Recently, room temperature ferromagnetism has been observed in GaMnP and other wide bandgap compound semiconductors. A next logical step is to incorporate these novel magnetic materials into heterostructures for the creation of spintronic devices. However, in order to create successful spin transistors or spin diodes, the tunable electronic properties of the ferromagnetic semiconductor must be addressed, such as carrier type and bandgap, just as in a non-spin device. In this paper, we will report on alternative doping strategies in the GaMnP system to produce variations in carrier type and bandgap, both by ion implantation and direct epitaxy. Specifically, magnetic (SQUID), transport (Hall), and structural (HRXRD, TEM) properties of AlGaMnP films with increasing bandgap will be presented with varying Mn levels. The variation of carrier type will also be addressed by doping the GaMnP films with SiBr_4 to create a majority population of electrons rather than holes. Hall effect measurements indicate electron concentrations of approximately $8 \times 10^{17}/\text{cm}^3$ for GaMnP films grown at 500°C with 5.5 % Mn as determined by Auger Electron Spectroscopy. Analysis by x-ray diffraction indicates that a high V-III ratio when doping with the SiBr_4 is important to suppress the formation of Mn_2P , the observed second phase in the GaMnP system. X-ray

rocking curve data will also be presented to quantify both the strain from Mn incorporation during epitaxy and the evolution of implant-induced lattice damage and recovery with annealing in ion implanted samples.

10:30 AM P6.5
FERROMAGNETISM IN DILUTE MAGNETIC SEMICONDUCTORS. Priya Mahadevan and Alex Zunger, NREL, Golden, CO.

Current interest in achievement of ferromagnetism at ambient temperatures has led to the investigation of the mechanism that stabilizes ferromagnetism in transition metal doped semiconductors. We report on three types of studies: (1) GGA calculations on the electronic structure of V-Ni in GaAs, GaN and GaP [1]: By varying the transition metal impurity as well as the semiconducting host independently [1], we have derived certain basic principles to understand ferromagnetism in these systems. We find a conventional double-exchange like mechanism at work in the case of systems like $\text{GaN}: \text{Mn}$ in which have dominantly Mn d character at the Fermi level. On the other hand, in systems such as GaAs:Mn which have dominantly As p character at the Fermi level, the mechanism is novel and is similar to what was proposed earlier for $\text{Sr}_2\text{FeMoO}_6$ [2]. (2) GGA calculations on substitutional + interstitial Mn complexes in GaAs [3]: We find the formation energy for Mn at an interstitial site is comparable to the energy required to substitute a Ga site with Mn under certain experimental conditions [3]. Charge neutral complexes between substitutional Mn and interstitial Mn are found to be strongly stabilized by Coulomb interactions. These complexes exhibit charge compensation, but surprisingly favor a ferromagnetic coupling between the substitutional Mn atoms. (3) Calculations of Mn in chalcogenides: In recent times, Mn doped CdGeP_2 has been found to exhibit room temperature ferromagnetism [4]. In Ref. [5] we have considered the interaction of intrinsic defects with substitutional Mn on Cd and Ge sites to elucidate under what experimental ferromagnetism can be achieved. References [1]. P. Mahadevan and A. Zunger, Electronic structure and ferromagnetism of 3d transition metal impurities in GaAs (submitted). [2] D.D. Sarma, P. Mahadevan, T. Saha-Dasgupta, S. Ray, A. Kumar, *Phys. Rev. Lett.* **85**, 2549 (2000). [3] P. Mahadevan and A. Zunger, Interstitial Mn impurity in GaAs: complexes and hole compensation (submitted). [4] G. A. Medvedkin, *Jpn. J. Appl. Phys.* **39**, L949 (2000). [5] P. Mahadevan and A. Zunger, *Phys. Rev. Lett.* **88**, 047205 (2002).

10:45 AM *P6.6
THERMODYNAMIC LIMITS TO THE MAXIMUM CURIE TEMPERATURE IN GaMnAs . W. Walukiewicz, and K.M. Yu, Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA; T. Wojtkowicz, University of Notre Dame, Notre Dame, IN and Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND; J.K. Furdyna, University of Notre Dame, Notre Dame, IN.

A number of recent studies have shown that the maximum Curie temperature, T_C is limited to about 110 K in GaMnAs . Since this T_C has been achieved through different thermal annealing cycles of samples with distinctly different Mn concentrations the question arises if this limit is of a fundamental nature. To address this issue we have studied the effect of the lattice site locations of Mn ions and free hole concentration on T_C . The location of the Mn ions in the crystal lattice was determined by simultaneous Rutherford backscattering spectrometry (RBS) and particle induced X-ray emission (PIXE) in the axial and planar channeling directions. The free hole concentration was measured using electrochemical capacitance voltage (ECV) profiler. We find that in GaMnAs the annealing induced changes of T_C originate from a redistribution of Mn atoms between different sites. An increase of the T_C and the hole concentration after low temperature annealing is associated with relocation of Mn from interstitial to substitutional and random precipitate sites. Our observed maximum T_C of 111 K corresponds to the maximum hole concentration of about 10^{21} cm^{-3} . The results suggest that the redistribution of the Mn atoms between different sites is controlled by the location of the Fermi energy. To test this suggestion we have investigated $\text{Ga}_{1-x}\text{Mn}_x\text{Be}_y$ samples in which the Fermi level position can be independently controlled by the Be doping. We find that for the hole concentrations close to the maximum level the increase in the Be doping results in a dramatic increase of the concentration of Mn interstitials and a reduction of T_C . These results confirm that for the hole mediated ferromagnetism in GaMnAs the maximum T_C of 110 K is achieved for the Fermi energy corresponding to 10^{21} cm^{-3} holes originating from uncompensated isolated acceptors.

11:15 AM P6.7
THEORY OF FERROMAGNETIC TRANSITION IN MAGNETICALLY DOPED SEMICONDUCTORS. V.K. Dugaev, M. Vieira, Inst Superior de Engenharia de Lisboa, Dept of Electronics and Communications, Lisbon, PORTUGAL; V.I. Litvinov, WaveBand Corp, Torrance, CA; J. Barnaś, Adam Mickiewicz Univ, Dept of

Physics, Poznań, POLAND.

We present results of analytical and numerical calculations of the Curie temperature in magnetically doped semiconductors. Two contributions to the indirect exchange interaction are taken into account: RKKY coupling via free carriers and a virtual-exchange coupling associated with acceptor impurity levels. Both contributions have essentially the same order of magnitude and even at a high carrier density, the virtual exchange mechanism is important and should be taken into account. We analyzed the role of disorder in impurity ferromagnetism. Two mechanisms are responsible for the disorder-induced variation of the ferromagnetic critical temperature: magnetic density fluctuation-induced effective coupling of spin density waves and decrease in the mean free path of carriers. Our conclusion is that interacting fluctuating modes comprise main contribution to suppression of the Curie temperature. We also calculated the fluctuation-induced corrections to the mean-field Curie temperature. This calculation helps to resolve a discrepancy between existing results of the mean field theory and a self consistent RPA approximation.

11:30 AM **P6.8**

ROOM-TEMPERATURE FERROMAGNETISM IN DIAMOND-LIKE TERNARY SEMICONDUCTORS. G.A. Medvedkin, Ioffe Physico-Technical Inst, Div of Solid State Physics, St. Petersburg, RUSSIA.

Recent two years a spectrum of spintronic materials was replenished with various three-component binary and multinary semiconductor compounds, which show room-temperature ferromagnetism. However, diverse and complex crystal structures of many new materials do not ensure at times worthy conditions for electron-spin transport through the boundary in heterostructures. Ferromagnetic and nonmagnetic semiconductors of a device quality should maintain non-scattered transport as in the bulk so through the perfect junction between heteropartners. The near-to-ideal heterojunction can be grown using relative crystal structures and close chemical and electronic properties of semiconductor compounds. This paper gives glance on plural ternary magnetic materials, especially ferromagnetic chalcocyanites, from point of view of semiconductor heterostructures grown to date or forecasted in frames of diamond-like family. The following consideration will be presented: Last trends in ferromagnetic chalcocyanites II-IV-V₂, both single crystal layers and bulk polycrystalline materials with above-room-temperature ferromagnetism; Magnetization loops and temperature dependences from 4 K up to 400 K for bulk and layer materials; Magnetic resonance spectra measured at low and up to room temperature; Further prospects to creation of new material compositions for spintronic applications based on Ga(1-x)Mn(x)As solid solutions with chalcocyanites.

SESSION P7: FERROMAGNETIC SEMICONDUCTORS - II

Chair: Alex Zunger

Wednesday Afternoon, December 4, 2002
Room 204 (Hynes)

1:30 PM ***P7.1**

CONTROL OF MAGNETIZATION ORIENTATION BY OPTICALLY GENERATED SPIN-POLARIZED CARRIERS IN III-V FERROMAGNETIC SEMICONDUCTORS. Akira Oiwa, Rai Moriya, Yukiko Kashimura, and Hiroo Munekata, Imaging Science and Engineering Laboratory, Tokyo Institute of Technology, JAPAN; Tomasz Słupiński, Institute of Experimental Physics, Warsaw University, POLAND; Yasuyoshi Mitsumori, Communications Research Laboratory, JAPAN.

Spin exchange interaction between carriers and local magnetic moments is an essential character for the occurrence of ferromagnetic ordering in III-V magnetic semiconductors. This exchange interaction opens ways to manipulate spin-related phenomena by charge and spin of carriers. In this report, we review the manipulation of the spin orientation of coupled local magnetic moments via the carrier spins that are generated optically in ferromagnetic (Ga,Mn)As thin films. Samples with in-plane magnetic anisotropy were grown by molecular beam epitaxy. Changes in magnetization were detected by measuring the anomalous Hall effect or the magneto-optical effect. When the circularly polarized light is irradiated, spontaneous Hall resistance (H=0 T) changes its sign according to the direction of circular polarization. This indicates that optically generated spin-polarized carriers collectively rotate Mn spins towards the normal axis. When the light is off, the Mn spins return back to the original in-plane orientation. The phenomenon has a sharp increase at the photon energy close to the band gap E_g of the samples. From the relation between the polarization direction and magnetization orientation, we infer that spin-polarized holes rotate Mn spins via the negative p-d exchange interaction. We stress that the observed change in

magnetization reaches to 15 % ($\Delta N_{Mn} \sim 10^{19} \text{ cm}^{-3}$) of saturation magnetization despite the small number of photogenerated carriers (10^{14} cm^{-3}). Rigorously stated, the observed change is accompanied by a small memorization effect. This indicates that the behavior involves some ferromagnetic process such as generation and annihilation of magnetic domains, and suggests the importance of ferromagnetic coupling between Mn spins. We will also discuss the dynamics of photoinduced spin rotation on the basis of experimental results obtained by the time-resolved Kerr rotation measurements.

2:00 PM **P7.2**

STUDY ON THE MAGNETIZATION OF GaSb/Mn DIGITAL ALLOYS. N. Kim, S.J. Lee, H. Luo, B.D. McCombe, SUNY at Buffalo, Department of Physics, Buffalo, NY; T.W. Kang, Dongguk University, Quantum-functional Semiconductor Research Center, Seoul, KOREA.

The precision of atomic layer epitaxy has led to the successful fabrication of ferromagnetic semiconductor digital alloys.^[1] The investigation of magnetization of GaSb/Mn digital alloys is presented, based on the structural characteristics of GaSb/Mn digital alloys that contain quasi-2D MnSb islands and randomly distributed Mn ions, as observed in cross sectional scanning tunneling microscopy studies.^[2] In addition to the spin-exchange interaction between free carriers and randomly distributed Mn ions, the interaction between carriers and MnSb islands, and ferromagnetism of MnSb islands are taken into account simultaneously. In this model, the exchange interaction between free carriers and MnSb islands is ferromagnetic, based on energy minimization.^[3] The interaction between free carriers and MnSb islands occurs because of the carrier wavefunction penetration into the islands, which is treated empirically with an effective exchange constant. This model explains the magnetization reversal of GaSb/Mn digital alloys at certain temperature range, observed recently, and qualitatively reproduces the temperature dependence of magnetization. The magnetization of GaSb/Mn digital alloys also strongly depends on the carrier concentration and the ratio of the number of isolated Mn ions and the number of Mn ions in quasi-2D MnSb islands.

[1] H. Luo et al., *Physica E* **12** 366-369 (2002).

[2] L. Whitman, private communication.

[3] I. Vurgaftman and J. R. Meyer, private communication.

2:15 PM **P7.3**

MAGNETIC EXCHANGE INTERACTIONS IN TRANSITION METAL DOPED III-V SEMICONDUCTORS. M. van Schilfgaarde, S.Y. Wu, H.X. Liu and N. Newman, Arizona State University, Dept of Chemical and Materials Engineering, Tempe, AZ.

Using the noncollinear local spin-density approximation, magnetic exchange interactions are studied in ideal Cr- and Mn-doped III-V semiconductors, including AlN, GaN, GaAs, GaP, and InP. Using a linear response technique, the LDA is mapped onto a Heisenberg form, and the parameters J are computed directly from the theory; the exchange interactions are computed for a variety of configurations in random and digital-doped III-V alloys. The disorder causes large fluctuations in J ; we show that the J 's depend strongly on the local doping environment. From the J 's, T_c is easily estimated in a simple mean-field approximation. More sophisticated modeling of finite temperature is also possible using a spin-dynamics approach. To accomplish this, we map the calculated J 's in a cluster expansion. It is seen that T_c has an intrinsic maximum with concentration for Mn dopants, but not for Cr dopants. Work is underway to experimentally test the validity of these predictions in the case of III-N semiconductors. Extensive characterization of the magnetic, electrical and optical properties as a function of Mn and Cr concentration will be reported.

2:30 PM **P7.4**

STRUCTURE AND CHEMISTRY OF ZnSe/GaMnAs/ZnSe HETEROSTRUCTURES GROWN ON GaAs. Guodan Lian, Elizabeth Dickey, Dept of Materials Science and Engineering, Pennsylvania State University, University Park, PA; Seung-Hyun Chun, Nitin Samarth, Dept of Physics, Pennsylvania State University, University Park, PA.

There is substantial interest in exploiting both the charge and spin of electrons in semiconductor spintronic devices. In particular, hybrid II-VI/III-V magnetic semiconductor heterostructures offer a possible route towards epitaxially grown heterojunction bipolar transistors since the optimal growth conditions for the different material components are compatible with each other. Here, we describe the structural characterization of n-ZnSe/p-Ga_{1-x}Mn_xAs/n-ZnSe heterostructures grown by molecular beam epitaxy on (100) GaAs substrates. The detailed structure and composition of the interfaces were analyzed using high-resolution electron microscopy (HREM), Z-contrast scanning transmission electron microscopy (STEM) and high-spatial-resolution electron energy loss spectroscopy (EELS). Although all layers were grown epitaxially, a high density of stack

faults was found in the ZnSe layer over GaMnAs, whereas the GaMnAs layer was defect free. The chemical abruptness of the interfaces was quantified by EELS, which showed inter-diffusion at both the ZnSe/GaMnAs and GaMnAs/ZnSe interfaces. Finally, we show how EELS also allows us to directly quantify both the concentration and valence state of Mn in the $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ layer, yielding $x = 0.07$ and a valence state of $2\pm$, as expected for acceptor behavior. This work was partially supported by DARPA and ONR.

3:15 PM P7.5

FERROMAGNETISM IN EPITAXIAL Co-DOPED TiO_2 ANATASE - DILUTED MAGNETIC SEMICONDUCTOR OR METALLIC CLUSTERS? S.A. Chambers, T. Droubay, S. Thevuthasan, D.E. McCready, S. Lea, C. Wang, C.F. Windisch, Jr., S.M. Heald, Fundamental Science Division, Pacific Northwest National Laboratory, Richland, WA; R.F.C. Farrow, R.F. Marks, J.-U. Thiele, M. Toney, L. Folks, S. Anders, M.G. Samant, IBM Almaden Research Center, San Jose, CA.

Co-doped TiO_2 anatase thin films have been of considerable interest because they exhibit ferromagnetism at and above room temperature and may be useful in spintronics. Anatase is a wide bandgap semiconductor that can be made n-type by creating oxygen vacancies. Therefore, doping with a few atomic percent Co may convert this material into an n-type diluted magnetic semiconductor (DMS). However, the possibility of metallic Co cluster formation must be explored, as this phenomenon would trivially explain the magnetism and render the material useless as a DMS. To this end, we have characterized epitaxial films grown by oxygen plasma assisted molecular beam epitaxy on $\text{LaAlO}_3(001)$ by core-level photoemission spectroscopy and microscopy, ion channeling, atomic force microscopy, transmission electron microscopy, x-ray diffraction, and x-ray absorption (XAS, XANES and EXAFS). We find absolutely no evidence for $\text{Co}(0)$ in any form. All Co is $\text{Co}(\text{II})$, which substitutes for $\text{Ti}(\text{IV})$ at cation sites, resulting in one oxygen vacancy per $\text{Co}(\text{II})$ to relieve strain. However, these vacancies do not produce free carriers. Rather, free electrons originate with oxygen vacancies resulting from an oxygen deficiency during growth. In addition to the above detailed materials characterization experiments, plausibility arguments based on the growth conditions preclude the survival of $\text{Co}(0)$ at the growth front. The alleged presence of Co clusters in Co-doped anatase grown by laser ablation may be an unfortunate consequence of using this growth method. The approach used here to hunt for magnetic metal clusters is applicable to the exploration of other candidate III-V and II-VI DMS materials.

3:45 PM P7.6

INVESTIGATION OF LATTICE OCCUPANCY OF Co ATOMS IN Co-DOPED DILUTE MAGNETIC OXIDE FILMS PREPARED BY PULSED LASER DEPOSITION V.N. Kulkarni, S.B. Ogale, S.R. Shinde, Y.G. Zhao, R. Choudhary, R.L. Greene and T. Venkatesan, CSR, Department of Physics, University of Maryland, College Park, MD.

Recent reports¹ on ferromagnetism in Co-doped transparent thin films of TiO_2 have generated considerable interest in diluted magnetic oxide systems because of their possible applications in the rapidly emerging area of spintronics. The precise mechanism of magnetism in these systems is still being debated in the literature. One key piece of information needed to reveal the underlying mechanism is the knowledge of lattice occupancy of Co atoms in the host matrix, whether substitutional or interstitial, or whether in the form of nano clusters. In this work we have employed the technique of Rutherford backscattering and ion channeling, which is very powerful in respect of such structural issues, to examine the thin films of anatase- $\text{Ti}_x\text{Co}_{1-x}\text{O}_2$ ($x=0$ to 0.15), rutile- $\text{Sn}_x\text{Co}_{1-x}\text{O}_2$ ($x=0$ to 0.15) and other oxide films prepared by pulsed laser deposition (PLD) technique on single crystalline (e.g. LaAlO_3 (001), Al_2O_3 (1102)) substrates. The undoped films of titanium oxide show excellent epitaxy with minimum yield of $<5\%$ while the doped films show a reasonably good epitaxy with Co atoms occupying non substitutional sites. For $\text{Sn}_x\text{Co}_{1-x}\text{O}_2$ films the growth is seen to occur about 2° off the substrate direction and the Co atoms are found to be non substitutional in this case as well. These results will be presented in this paper along with the magnetization and X-ray diffraction data, and their implications for the underlying mechanism of magnetism in these systems will be discussed.

Work supported under NSF-MRSEC-DMR 00-80008

1. Y. Matsumoto et al., *Science* **291**, 854(2001)

4:00 PM P7.7

FERROMAGNETISM IN TM-DOPED SEMICONDUCTING OXIDES Mat Ivill, David Norton, Stephen Pearson, B.-S. Jeong, Young Woo Heo, V. Varadarajan, Univ of Florida, Dept of Materials Science and Engr, Gainesville, FL; Arthur Hebard, N. Theodoropoulou, University of Florida, Dept of Physics, Gainesville, FL; Lynn Boatner, Solid State Div, Oak Ridge National Laboratory,

Oak Ridge, TN; Y. Park, Seoul National Univ, Seoul, SOUTH KOREA; R. Wilson, Stevenson Ranch, CA.

Transition metal doped semiconductors offer significant potential in providing spin-based functionality. Theoretical predictions suggest that carrier-mediated ferromagnetism should be possible in spin-doped semiconducting oxides, most notably Mn-doped ZnO . In this paper, we report on the synthesis and properties of transition metal-doped semiconducting oxides, including ZnO and Cu_2O . While previous efforts report no ferromagnetism in Mn-doped ZnO that is n-type due to group III impurities (consistent with theory), we find ferromagnetism in n-type ZnO that is co-doped with Mn and Sn. Hysteresis was observed in magnetization versus field curves for Mn-implanted n-type ZnO : Sn . Differences in zero field-cooled and field-cooled magnetizations persists up to ~ 150 K for Sn-doped ZnO crystals implanted with 3 at % Mn. In addition, we find ferromagnetism in Mn-doped Cu_2O epitaxial films. The properties of these films, including efforts to delineate the origin of ferromagnetic behavior, will be reported. These results indicate that semiconducting oxides doped with transition metals may prove promising as ferromagnetic semiconductors for spintronics.

4:15 PM P7.8

STRUCTURE AND PROPERTIES OF DILUTE MAGNETIC SEMICONDUCTORS FORMED BY IMPLANTATION AND PULSED LASER MELTING M.A. Scarpulla, O.D. Dubon, University of California at Berkeley, Dept of Materials Science and Engineering, Berkeley, CA; K.M. Yu, O. Monteiro, Z. Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA; M. Pillai, M.J. Aziz, Harvard University, Division of Engineering and Applied Sciences, Cambridge, MA; M.C. Ridgway, Australian National University, Dept of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, Canberra, AUSTRALIA.

We present a study of the structural, electrical, and magnetic properties of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ thin films formed by Mn ion implantation into GaAs at concentrations approaching $10^{21}/\text{cm}^3$ followed by pulsed laser melting (PLM). Results from multiple characterization techniques, including SQUID magnetometry, electrochemical capacitance-voltage profiling, transmission electron microscopy, and Rutherford backscattering spectrometry are presented. While rapid thermal annealing of Mn-implanted GaAs is known to lead to the formation of MnAs and GaMn nano-particles, second phase formation is suppressed in our experiments due to the nanosecond time scales involved in PLM. The films are shown to be epitaxial with high levels of Mn substitutionality. Hysteretic magnetic behavior with Curie temperatures in excess of 75 K are observed. The effects of low temperature post-growth annealing are examined, as well as the effects of co-implantation with the acceptor species carbon. The application of this technique to other material systems will also be addressed.

4:30 PM P7.9

MICROSTRUCTURAL INVESTIGATIONS OF FERROMAGNETIC $(\text{In},\text{Mn})\text{As}$ GROWN BY METALORGANIC VAPOR PHASE EPITAXY A.J. Blattner, P.L. Prabhuramirashi, V.P. David, B.W. Wessels, Northwestern University, Department of Materials Science and Engineering and Materials Research Center, Evanston, IL.

The microstructure of $\text{In}_{1-x}\text{Mn}_x\text{As}$ diluted magnetic semiconductor (DMS) thin films grown using metalorganic vapor phase epitaxy (MOVPE) on $\text{GaAs}(001)$ substrates was investigated. Single-phase films, as determined by x-ray diffraction, exhibited room temperature ferromagnetism with $T_c = 333$ K for $x = 0.01$ –0.10. Such a high Curie temperature for a III-V DMS has previously been attributed to the presence of MnAs precipitates. In order to investigate this possibility in our films, we have performed microstructural evaluations using transmission electron microscopy (TEM). Microanalysis of a single phase film with a $T_c = 333$ K was carried out using several analytical techniques such as electron energy loss spectroscopy (EELS), energy-filtered TEM, and energy dispersive x-ray spectrometry (EDS) to map Mn distribution within the films. EDS line scans (probe size < 4 nm) across a plan view sample indicated homogeneous distribution of Mn in a film with $x = 0.01$ grown at a substrate temperature of 500°C. No MnAs nanoprecipitates were observed. TEM diffraction indicated a zinc blende structure corresponding to $\text{In}_{1-x}\text{Mn}_x\text{As}$. Films grown at lower substrate temperatures ($T_s \leq 475^\circ\text{C}$) exhibited the formation of ellipsoidal shaped MnAs precipitates within the $\text{In}_{1-x}\text{Mn}_x\text{As}$ matrix. This work indicates that single-phase $\text{In}_{1-x}\text{Mn}_x\text{As}$ can be formed by MOVPE that exhibit room temperature ferromagnetism.

SESSION P8: HALF-METALS AND SPIN INJECTION IN SUPERCONDUCTORS

Chair: Christopher J. Palmstrom
Thursday Morning, December 5, 2002
Room 204 (Hynes)

8:30 AM P8.1

A NEW FAMILY OF HALF-METALLIC FERROMAGNETS. A. Holm, S. Kauzlarich, W. Pickett, University of California Davis, Davis, CA; S.A. Morton, G.D. Waddill, University of Missouri-Rolla, Rolla, MO; J.G. Tobin, Lawrence Livermore National Laboratory, Livermore, CA.

X-ray magnetic circular dichroism measurements (MXCD) indicate full, perfect spin alignment in the Mn (five aligned spins) and suggest that $\text{Yb}_{14}\text{MnSb}_{11}$ is a half-metallic ferromagnet. The compound is isostructural to $\text{Ca}_{14}\text{AlSb}_{11}$, with the Mn occupying the Al site in the $[\text{AlSb}_4]^{9-}$ discrete tetrahedral anionic unit. Bulk magnetization measurements exhibit a saturation moment of $3.9 \pm 0.02 \mu_B$ per formula unit consistent with 4 unpaired spins and implying a Mn^{3+} , high spin d^4 state. XMCD measurements reveal that the Mn_{23} is strongly dichroic, the Sb shows a weak dichroism that is antialigned to the Mn, and the Yb_{45} shows no dichroism. Comparisons of the Mn spectra with theoretical models for Mn^{3+} show excellent agreement. The bulk magnetization can be understood as full spin alignment (five spins up) of the Mn^{3+} with cancellation of one spin by an antialigned moment from the Sb 5p band of the Sb₄ cage surrounding the Mn.

8:45 AM P8.2

SPIN POLARIZED PHOTOEMISSION STUDY OF MAGNETITE FILMS: EVIDENCE FOR HALF METALLIC BEHAVIOR. S.A. Morton, G.D. Waddill, University of Missouri-Rolla; S. Kim, Ivan Schuller, University of California San Diego; S. Chambers, Pacific Northwest National Laboratory; J.G. Tobin, Lawrence Livermore National Laboratory.

Many materials have been predicted theoretically to be half metallic, i.e. displaying 100% electron polarization at the Fermi level. Such materials have attracted considerable theoretical, experimental, and technological interest as potential pure spin sources for use in spintronic devices; however remarkably little truly definitive experimental evidence for half metallic behavior has yet emerged. One of the most promising of these candidate materials is magnetite, Fe_3O_4 , which has a long history of existing technological applications and has a relatively simple structure in comparison to many of the other candidate materials that makes it both easier to prepare experimentally and to model theoretically. However, to-date, measurements of the Fermi-edge polarization of Fe_3O_4 by techniques such as spin polarized photoemission have yielded values considerably lower than the required 100%. By conducting spin resolved depth profile measurements and comparing the results to theoretical band structure calculations we have demonstrated that Fe_3O_4 exhibits a semiconducting non-magnetic surface re-construction which significantly reduces the observed polarization but that, in contrast, the underlying bulk material is in fact very strongly polarized. Indeed, once the effects of this surface reconstruction are taken into account by theoretical models of the polarization an excellent match is obtained between the experimental spin resolved spectra and simulated spectra generated from theoretical spin polarized band structure calculations. Hence our results strongly support the notion that Fe_3O_4 is indeed a half-metallic material suitable for use in a new generation of spintronic devices. Work is now in progress to extend these experiments to other half metallic candidate materials such as CrO_2 .

9:00 AM P8.3

ANOMALOUS MAGNETOTRANSPORT PROPERTIES OF EPITAXIAL FULL HEUSLER ALLOYS. M.S. Lund, J.W. Dong, J. Lu, X.Y. Dong, C.J. Palmström and C. Leighton, Dept. of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN.

Full Heusler alloys of general formula A2MnB have received renewed attention lately due to the fact that they are candidate half-metallic ferromagnets. In contrast to systems like CrO_2 (which has been demonstrated to be a highly spin polarized material) the magnetotransport properties of full Heusler alloy epilayers are largely unknown. We report the temperature dependent magnetotransport properties of epitaxial films of the full Heusler alloys Ni_2MnGa , Ni_2MnGe and Ni_2MnAl , grown by molecular beam epitaxy on (001) GaAs. Variation of the species B (from Ga to Ge to Al) allows us to access various magnetic ground states. Structural characterization data from X-ray diffraction, Rutherford backscattering, and cross-sectional transmission electron microscopy attest to the structural quality. The ferromagnetic alloys (Ni_2MnGa and Ni_2MnGe) exhibit anomalous behavior in the temperature dependence of the resistivity and magnetoresistance. The zero magnetic field resistivity reaches a peak value in the vicinity of the Curie temperature and displays a crossover to semiconductor-like temperature dependence at high temperatures. At the same point we observe a negative magnetoresistance, which appears to be related to classic spin disorder scattering. We also observe another negative

magnetoresistance component (of unknown origin), which persists down to low temperatures and is present in all samples, regardless of whether they are ferromagnetic. At temperatures below 20 K the resistivity shows an upturn that is shown to be consistent with electron-electron interactions in the presence of disorder. In light of the large absolute resistivity values, the anomalous behavior at high temperatures, and the upturn at low temperatures, we suggest that these Heusler alloy films, far from being conventional metals, are in fact strongly disordered electronic systems close to a metal-insulator transition. We speculate that the electronic properties of these materials are every sensitive to effects such as antisite disorder. Work supported by NSF MRSEC.

9:15 AM P8.4

COHERENT MAGNETIZATION ROTATION AND PHASE CONTROL BY ULTRASHORT OPTICAL PULSES IN CrO_2 THIN FILMS. Qiang Zhang, A.V. Nurmiikko, Division of Engineering and Department of Physics, Brown University, Providence, RI; A. Anguelouch, G. Xiao, Department of Physics, Brown University, Providence, RI; A. Gupta, IBM T.J. Watson Research Center, Yorktown Heights, NY.

The large spin polarization ($\sim 96\%$) in CrO_2 single crystal epitaxial films is responsible for static magnetization reversal by coherent rotation. We have applied photoexcitation by ultrashort laser pulses to single crystal thin CrO_2 films to trigger coherent transient magnetization rotation on a subnanosecond time scale, in macroscale single domains. By choosing a photon energy below the minority spin gap, photons are effective in exciting majority spins. The mechanism behind the photoexcitation originates from the modulation of the magnetocrystalline anisotropy by nonthermal hot electron spins. Moreover, by applying the photoexcitation by pairs of temporally separated pump pulses, the transient precession of the magnetization can be phase controlled, depending on the time separation between the pulses.

9:30 AM *P8.5

SPIN POLARIZATION OF CrO_2 ACROSS AN ARTIFICIAL BARRIER: AN ANALYSIS WITH ZEEMAN-SPLITTING OF ANDREEV CONDUCTANCE. Peng Xiong, J.S. Parker, J.G. Braden, S.M. Watts, P.G. Ivanov, P. Schliemann, and S. von Molnár, Department of Physics and MARTECH, Florida State University, Tallahassee, FL.

We have carried out a systematic measurement of the spin polarization of epitaxial CrO_2 films using a planar junction geometry, mimicking a real device structure, with superconducting counter electrodes. Using a chemical treatment of the CrO_2 surface, we were able to controllably fabricate junctions from metallic contact to tunnel junctions. The junction conductance is analyzed independently using Andreev reflection at zero field and spin-resolved transport in the presence of Zeeman splitting. The latter method developed in this work, which takes into account the Maki dressing in superconducting pairing, is applicable to junctions of arbitrary barrier strength and ferromagnet of arbitrary spin polarization. Both analyses yielded consistent, close to full spin polarization for CrO_2 at the artificial interface regardless of the barrier strength [1], in contrast to results from point contact measurements [2]. Moreover, we demonstrated that $\sim 100\%$ spin polarized current can be injected across this barrier into the superconductor. [1] J.S. Parker, S.M. Watts, P.G. Ivanov, and P. Xiong; Phys. Rev. Lett. 88, 196601 (2002). [2] Y. Ji et. al., Phys. Rev. Lett. 86, 5585 (2001).

10:30 AM *P8.6

STM PROBE OF PAIR-BREAKING BY SPIN-INJECTION IN CUPRATE/MANGANITE THIN-FILM STRUCTURES. John Wei, Department of Physics, University of Toronto, CANADA.

I will report on recent progress using cryogenic STM spectroscopy to probe the effects of spin-injection on the high-T_c pairing in cuprate/manganite thin-film heterostructures. Samples of various injection geometries were measured, using both DC and pulsed currents, to rule out any Joule-heating effects. The STM spectra were analyzed with quasiparticle-tunneling and Andreev-reflection formalism for a d-wave pairing symmetry, to look for signatures of: 1) quasiparticle non-equilibrium; 2) order-parameter suppression; 3) broken time-reversal symmetry. The STM data is also compared with recent transport measurements, which indicate systematic critical-current suppression and non-trivial junction transmission. Our results provide strong microscopic evidence for magnetic pair-breaking by the spin-injection, and suggest promising new ways both to study and to exploit this dynamic effect.

11:00 AM *P8.7

MAGNETIC FIELD SCALING OF THE CONDUCTANCE OF EPITAXIAL CUPRATE MANGANITE BILAYERS. Anand Bhattacharya, P.A. Kraus and Allen M. Goldman, School of

Physics and Astronomy, University of Minnesota, Minneapolis, MN.

Current-voltage characteristics of interfaces between epitaxially grown manganite ferromagnets and cuprate superconductors have been measured as a function of temperature and magnetic field. The measured characteristics are similar to those predicted by theories of transport across nearly transparent contacts between highly spin-polarized ferromagnets and d-wave superconductors. However, the conductance-voltage curves at different magnetic fields can be made to scale in striking and unusual ways, not predicted by any theory. Theoretical understanding of how a voltage develops across an interface during current injection between a ferromagnet and a superconductor in the presence of long-lived out-of-equilibrium spins in the superconductor is lacking at the present time. We shall present our current understanding of this question.

11:30 AM **P8.8**

STRAIN AND DEVICE PERFORMANCE OF $\text{Sr}_2\text{FeMoO}_6$ THIN FILMS. **A. Venimadhav**, Dept of Materials Science and Metallurgy, Cambridge University, Cambridge, UNITED KINGDOM; J. P. Attfield, Dept of Chemistry, Cambridge University, Cambridge, UNITED KINGDOM; M. Blamire, Dept of Materials Science and Metallurgy, Cambridge University, Cambridge, UNITED KINGDOM.

$\text{Sr}_2\text{FeMoO}_6$ (SFMO) is ferromagnetic metallic oxide with a Curie temperature of 150 K above the room temperature. It has been predicted to be a half-metallic by band structure calculations and is of particular interest as a source of spin polarized electrons for room temperature spintronics, but the high deposition temperature and instability of the optimum phase have meant that the growth of high quality thin films has been achieved only in a few laboratories. We have grown thin films of SFMO by pulsed laser deposition on SrTiO_3 (STO) (100) and LaAlO_3 (100) and characterized them by XRD, AFM, conductivity and magnetic measurements. Unlike previous reported processes, our films are deposited in an Ar/O_2 gas mixture during the deposition; the pressure and gas mixture are found to be crucial for obtaining the correct SFMO phase. The films are epitaxial and smooth on both substrate types; on STO they show ferromagnetic behavior with a Curie temperature of 380 K. Metallic conductivity is observed down to 80 K with a slow rise in resistivity. We see a large magnetoresistance at 77 K. This paper will present detailed results on the conductivity and magnetoresistance of plain SFMO and films deposited on bi-crystal substrates. The implications for devices will be discussed.

11:45 AM **P8.9**

MAPPING OF MAGNETIC PHASE DIAGRAMS OF HEUSLER ALLOY SYSTEMS USING A COMPOSITION SPREAD TECHNIQUE. **O. Famodu**, J.C. Read, M. Aronova, F.C. Wellstood, M. Wuttig, and I. Takeuchi, Univ of Maryland, College Park, MD.

We have developed a composition-spread technique for mapping the composition-structure-property relationship in a variety of magnetic metallic alloys. A three-gun UHV magnetron co-sputtering system is used for creating co-deposited composition spreads on 3" Si wafers. Wavelength dispersive spectroscopy is used to map the composition distribution of the spread wafers directly onto ternary phase diagrams. Scanning SQUID microscopy is used to perform quantitative magnetization mapping at room temperature. Scanning x-ray microdiffractometry allows mapping of the phase distribution on the spread wafers. We are exploring various ternary systems which contain Heusler alloys. In the Ni-Mn-Ga system, we observe a large high magnetization region (up to ≈ 300 emu/cc) that stretches from the Heusler composition, Ni_2MnGa , to the center of the phase diagram. In the Co-Mn-Ga system, a very high magnetization (> 1000 emu/cc) region is observed near the Co corner of the phase diagram, but it drops off as it nears the Heusler composition, Co_2MnGa . In the Ni-Mn-Ga system, we have also mapped the compositions that undergo reversible martensitic phase transitions, thus identifying regions that display the ferromagnetic shape memory effect.

SESSION P9: FROM MANGANITES TO ORGANIC SPINTRONIC MATERIALS - I

Chairs: Anand Bhattacharya and Arthur J. Epstein
Thursday Afternoon, December 5, 2002
Room 204 (Hynes)

1:30 PM **P9.1**

PHOTO-INDUCED MAGNETISM IN $\text{La}_{0.5}\text{Pr}_{0.5}\text{CrO}_3$. **Masato Arai**, Mitsuru Izumi, Tokyo Univ. Merc. Marine, Lab. Appl. Phys., Koto-ku, Tokyo, JAPAN; Osami Yanagisawa, Yuge National Col. of Maritime Technology, Yuge, Ehime, JAPAN.

In a perovskite-type chromite $\text{La}_{0.5}\text{Pr}_{0.5}\text{CrO}_3$ we have found that the electron-spin resonance (ESR) appears during the illumination of near-infrared light. This photo-induced and transient magnetization is

temperature dependent with the characteristic thermal activation energy of 130 meV below the spin-canted antiferromagnetic transition temperature 261 K. At room temperature the photo-induced ESR intensity is remarkably enhanced. We interpret this is coming from the photo-excited carrier-induced magnetism. By analogy with the manganites, the irradiated photons excite the t_{2g} electrons to the e_g state in Cr^{3+} ($3d^3$) which is similar to Mn^{4+} . Either spin is $S=3/2$ in t_{2g} state. The present results may open up an intriguing collective photo-induced magnetism, the creation and control of spin polarization and spin-polarized transport with near-infrared light.

1:45 PM **P9.2**

ELECTRIC FILED MODULATION OF DOUBLE EXCHANGE FERROMAGNETISM AT ROOM TEMPERATURE IN THE PEROVSKITE MANGANITE BASED SPINTRONIC DEVICE. **Hidekazu Tanaka**, Inst. of Scientific and Industrial Research, Osaka Univ., Osaka, JAPAN, and PRESTO, Japan Science and Technology Corporation; Teruo Kanki, Jun Zhang, Tomoji Kawai, Inst. of Scientific and Industrial Research, Osaka Univ., Osaka, JAPAN.

We report on the electrical modulation of double exchange ferromagnetism at room temperature in hole doped manganites of a metal oxide p-n junction constructed by laser molecular beam epitaxy technique. In this $(\text{La}_{0.9}\text{Ba}_{0.1})\text{MnO}_3$ (film)/Nb-doped SrTiO_3 (single crystal) p-n junction, the temperature dependence of the junction resistance shows a metal-insulator transition whose temperature, corresponding to that of ferromagnetic transition, is hugely modulated from 290 K to 340 K by a bias voltage increasing from +1.0 to +1.8 V. The magnetoresistance can also be modulated electrically from 5% to 30% while decreasing bias voltage from 3.0 V to 1.0 V at 10 K under the magnetic field of 5 T. As a further development, by optimizing the junction fabrication condition, we achieved fabrication of all-perovskite oxide film p-n junction, composed of $(\text{La}_{0.9}\text{Ba}_{0.1})\text{MnO}_3$ and $(\text{Sr}_{0.99}\text{La}_{0.01})\text{TiO}_3$ films, which exhibits both room temperature ferromagnetism and good rectifying properties without inserting any insulator layer. In addition, by using frequency shift- non contact magnetic force microscope, nucleation of nanoscale magnetism in the $(\text{La},\text{Ba})\text{MnO}_3$ thin film just at room temperature was observed, and its electric field modulation will be also presented.

2:00 PM **P9.3**

COMPOSITE MANGANITE THIN FILMS: AN APPROACH TO CONTROL THE MAGNETOTRANSPORT PROPERTIES. **V. Moshnyaga**, S.A. Köster, B. Damaske and K. Samwer, I. Physikalisches Institut, Universität Göttingen, GERMANY; O. Shapoval and A. Belenchuk, Institute of Applied Physics, Chisinau, MOLDOVA; O.I. Lebedev and G. van Tendeloo, EMAT, University of Antwerp (RUCA), BELGIUM.

Nano-composite epitaxial films of $(\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3)_{1-x}(\text{MgO})_x/\text{MgO}(100)$ and polycrystalline films of $(\text{La}_{0.75}\text{Sr}_{0.25}\text{MnO}_3)_{1-x}(\text{MgO})_x/\text{Al}_2\text{O}_3$ were both prepared by a metalorganic aerosol deposition technique. Epitaxial LCMO/MgO composites show that the magnetotransport is controlled by 3D mechanical stresses, originating from the second phase MgO. At the percolation threshold, $x=0.3$, an infinite insulating MgO cluster induces the structural phase transition in the LCMO phase from the orthorhombic Pnma structure ($x<0.3$) to a pseudocubic R3c one ($x>0.3$). Completely different behavior exhibit the polycrystalline LSMO based composites. At a low amount of MgO, $x\sim 0.02$, the electrical transport is now governed by a MgO-tunnel barrier located at the former grain boundaries. This provides a pronounced spin polarized tunneling magnetoresistance (TMR-effect) at low magnetic fields. Different to TMR-junctions produced in multilayers, we discuss here a lateral network of tunneling barriers completely made from oxides. Support by the DFG via SFB 602, TPA2 is acknowledged.

2:15 PM **P9.4**

INVESTIGATION OF ELECTRON-PHONON INTERACTION AND ELECTRON DENSITY OF STATES IN SINGLE CRYSTALS OF $\text{La}_{0.75}\text{Sr}_{0.25}\text{MnO}_3$ AND $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ BY POINT CONTACT SPECTROSCOPY AND SCANNING TUNNELING SPECTROSCOPY. **J. Mitra**, A.K. Raychaudhuri, Department of Physics, Indian Institute of Science, Bangalore, INDIA.

Rare earth manganites, with the general chemical formula $\text{Re}_{1-x}\text{Ae}_x\text{MnO}_3$, have attracted much attention because of the variety of transport and magnetic properties they exhibit, like Colossal magnetoresistance and Charge-ordering. One of the crucial factors governing the physics of manganites is the strong electron-phonon coupling, due to Jahn-Teller distortion around the Mn^{3+} ions. To probe the electron-phonon coupling in these systems we carried out Point Contact Spectroscopy on $\text{La}_{0.75}\text{Sr}_{0.25}\text{MnO}_3$ and $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ at 4.2 K. Results show that the strong dynamic electron-phonon coupling can arise from optical phonons involving various modes of vibrations of the MnO_6 octahedron. Thus giving rise to a large value for the electron-phonon coupling constant λ . We also

probe the electron density of states in the above samples across their respective Curie temperatures (T_c) in order to explain the sharp decrease in resistivity associated with the paramagnetic to ferromagnetic metallic phase transition. We conclude that this sharp change of resistivity near T_c is associated with a sharp change in the electron-density of states in the system. We discuss the impact of these observations in view of likely physical processes taking place in the manganites.

2:30 PM P9.5

COLLECTIVE MAGNON-POLARON AND LOCALIZED SPIN-POLARON REGIMES IN THE SPECIFIC HEAT AND ELECTRICAL RESISTIVITY OF $La_{0.8}Y_{0.1}Ca_{0.3}MnO_3$ IN ZERO MAGNETIC FIELD: THE EFFECT OF $O\text{-}Mn\text{-}O$ BOND ENVIRONMENT. M. Ausloos, S. Dorbolo, R. Cloots, SUPRAS, Université de Liège, Liège, Euroland and A. Gilabert, Université de Nice-Sophia Antipolis, Nice, FRANCE.

$La_{0.8}Y_{0.1}Ca_{0.3}MnO_3$, an ABO_3 perovskite manganite oxide, exhibits remarkable non trivial behaviors in the vicinity of the sharp peak found in the resistivity ρ as a function of temperature T in zero magnetic field. The various features (λ -like peaks) seen on $d\rho/dT$ are discussed in terms of competing magnetic and electronic phase transitions. They are shown to be perfectly related to the $Mn\text{-}O\text{-}Mn$ bond environment, i.e. they depend on the content of the four A crystallographic sites. The specific heat c of such a compound is also examined from 50 till 200 K and present the same features as $d\rho/dT$. Thus we indicate a remarkable agreement for the Fisher-Langer formula, i.e. $c \sim d\rho/dT$ at second order phase transitions. Therefore the $O\text{-}Mn\text{-}O$ bond environment explains the complex features of the transition region like in Attfield model. A Ginzburg-Landau type theory is presented for incorporating such concurrent phase transitions. Moreover in the low temperature conducting ferromagnetic phase, a collective magnon signature ($c \approx T^{3/2}$) is found beside the localized spin scattering term of a double exchange model. At high temperature, $c \approx T^{2/3}$; this is discussed in terms of the fractal dimension of the conducting network of the weakly conducting (so-called insulating) phase and Orbach estimate of the excitation spectral behaviors. To consider both independent spin scatterings and collective spin scatterings is thus emphasized.

SESSION P10/NN7: JOINT SESSION
FROM MANGANITES TO ORGANIC SPINTRONIC
MATERIALS - II
Chairs: Anand Bhattacharya and Arthur J. Epstein
Thursday Afternoon, December 5, 2002
Room 204 (Hynes)

3:15 PM *P10.1/NN7.1

HYBRID SPINTRONICS: A NEW PERSPECTIVE FOR ORGANIC SEMICONDUCTORS IN SPINTRONICS. I. Bergenti, V. Dedi, P. Nozar, G. Ruani, M. Murgia, C. Taliani, ISMN-Bo, CNR, Bologna, ITALY.

We show a new approach to Spintrronics by using organic semiconductors as active transport materials in combination with novel spin polarised (SP) electrodes made of a $La0.7Sr0.3MnO_3$ (LSMO) thin film which is a ferromagnetic metal at RT. Sextithiény is deposited by UHV deposition on a nanostructured channel of a planar LSMO spin-valve test pattern. At zero magnetic field the LSMO electrodes are randomly oriented, while in the magnetic field the SP are parallel. By inserting a 3.4 kOe magnetic field we observe indeed a 30% drop of resistance (MR) for a channel length L of 140 nm. By increasing L the MR drops by 7-10% at 200nm and eventually vanishes at 300nm. The room temperature spin transfer coherence length is estimated to be about 200-300nm. This is the first evidence of spin coherent injection and transfer in organic semiconductors (1). Other organic semiconductors have been investigated including Zn-Phtalocyanine, Alq3 and TPD. LSMO electrodes have been also applied to an Organic Light Emitting Diode (OLED) configuration showing efficient charge injection; electroluminescence turns on at 6V. This finding opens the possibility to control the recombination spin statistics of the OLED improving therefore the total electroluminescence efficiency by forcing the formation of singlets rather than triplets. 1) V. Dedi et. al., Sol. St. Commun., 122, (2002), 181; USA patent no: 6.325.914.

3:45 PM P10.2/NN7.2

ORGANIC SEMICONDUCTOR MAGNETO-ELECTRONICS.
Albert H. Davis, Konrad Bussmann, Materials Physics Branch, Naval Research Laboratory, Washington, DC.

Developments in magneto-electronics are advancing by combination of once disparate areas of research in magnetic materials, semiconductor electronics, and opto-electronics. We expand on this theme by

exploring the integration of magnetic materials with organic semiconductors. It is expected the low atomic mass of these materials will minimize spin-relaxation due to spin-orbit coupling so that utility can be made of spin-dependent phenomena in these structures. We pursue the manipulation of spin-polarized holes and electrons in an effort to generate a magnetic field dependent luminescence in an OLED device. We have fabricated various organic light emitting structures consisting of ferromagnetic electrodes and luminescent organic semiconductors and show that both hole and electron injection from magnetic electrodes is possible. We present luminescence data as a function of drive voltage, temperature and magnetic field as well as current-voltage data for these devices. Finally, we discuss fabrication issues, future studies and applications.

4:00 PM *P10.3/NN7.3

SPIN-DRIVEN RESISTANCE IN ORGANIC-BASED MAGNETIC SEMICONDUCTOR V[TCNE]x (x~2). N.P. Raju, Vladimir N. Prigodin, Kostia I. Pokhodnya, Arthur J. Epstein, Department of Physics and Department of Chemistry, The Ohio State University, Columbus, OH; Joel S. Miller, Department of Chemistry, University of Utah, Salt Lake City, UT.

V[TCNE]x (x~2, TCNE = tetracyanoethylene) is the first organic-based magnetic semiconductor. It orders magnetically at Curie temperature up to ~ 125 C and has room temperature resistivity $\sim 10,000$ ohm-cm. Here we present the results of the first study of an increase in resistance with applied magnetic field (positive magnetoresistance) for V[TCNE]x at room temperature, up to $\sim 0.7\%$ at $H = 6$ kG. The linear dependence on applied magnetic field differs from predictions of conventional disordered semiconductors. Results are discussed in context with results from dc magnetization, EPR, and XPS/UPS studies. Squeezing of electron wave functions by magnetic field (a mechanism for the positive magnetoresistance in conventional disordered semiconductors) predicts a magnetoresistance quadratic in magnetic field and three orders of magnitude less than the observed value. The temperature dependence of the magnetoresistance also differs from conventional expectations. We suggest that the initial metallic half-filled p^* electronic [TCNE]- band is split by strong Coulomb repulsion into two subbands. Electrons occupying the lowest subband are coupled antiferromagnetically with the three 3d electrons of VII and as a result the p^* subbands are oppositely spin polarized. The present model explains the observed anomalous value of magnetoresistance and its variations with magnetic field and temperature. The potential for use of organic-based magnetic semiconductors in spintronic devices is discussed. *Supported in part by U.S. Army Research Office Grant No. DAAD19-01-1-0562, Department of Energy Grant No. DE-FG02-01ER45931, DE-FG03-93ER45504, and DARPA.